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REPORT

ON THE

COMPRESSIVE STRENGTH, SPECIFIC GRAVITY,

AND

RATIO OF ABSORPTION

OF THE

BUILDING STONES

IN THE UNITED STATES,

BY

Q. A. GILLMORE,

LIEUT.-COL. CORPS OF ENGINEERS; BVT.-MAJ.-GEN., U. S. A.; AUTHOR OF "TREATISE ON LIMES, CEMENTS, ETC.;" "TREATISE ON COIGNET BETON AND ARTIFICIAL STONES;" AND "TREATISE ON ROADS, STREETS, AND PAVEMENTS," ETC., ETC., ETC.

OFFICIAL REPORT TO THE CHIEF OF ENGINEERS, U. S. ARMY.

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United States Engineer Office,
New York, *August* 10, 1875.

General: I have the honor to state that my tests to determine the compressive strength, specific gravity, and ratio of absorption of the building-stones in the United States in most general use have been considerably extended since my report of July 30, 1874. The methods pursued and the results obtained, inclusive of those first reported, are embodied, and to some extent discussed, in the paper herewith submitted.

My assistant, Mr. Louis Nickerson, had immediate charge of all the experiments and tests made during the past year, and I am indebted to him for valuable suggestions and zealous co-operation during the progress of the work.

Very respectfully, your obedient servant,

Q. A. Gillmore,
Lieut. Col. of Engineers, Bvt. Maj. Gen., U. S. A.

Brig. Gen. A. A. Humphreys,
Chief of Engineers, U. S. A.

REPORT.

FORM OF SPECIMENS AND METHOD OF TESTING.

Many of the specimens were delivered from the quarries in the form of cubes, measuring 2 inches each way, but the greater part have been wrought into form at Fort Tompkins. The desire has been to get average specimens, rather than to have the quarries picked for fine pieces, and it is thought that the attempt has been in general successful. Each cube was placed between two cushion-blocks of soft pine wood, 2 inches by 2 inches square, and slightly more than ¼ inch in thickness, one on the top and the other under the bottom; the grain of the wood being parallel in each to the other—though no difference was observed when this was changed, as regards amount of record. This arrangement caused the pressure to come more gradually upon the stone, and the cushions, becoming much indurated by the effects of pressure, to some extent took the place of the mortar used in actual building.

For iron and wood, Hodgkinson has shown that trial specimens should be at least one and one-half times as high as the width of bed; but stone, except when used as columns, is usually laid of less height than bed, and the cubical form of specimens adopted for the experiment affords sufficient security for the angular breakage which he proved to be necessary for a true result. This latter fact is corroborated by subsequent experiments.

The cubes recorded in the general tables were brought to a true, smooth, and regular, but not a polished, surface. The granites and marbles, however, embraced in the tables under the head of "Sundry special experiments," were carefully rubbed down to the border of a polish, because in these great homogeneity and fineness, especially of bed-surface, was rather desired than the true building-strength of the stone. This latter plan undoubtedly increased the resistance. It is not, however a *high* valuation that we want for the general table, but a safe one; and, moreover, we desire to arrive at some knowledge of the resistance which the rock will have when applied in the usual manner in a wall. The mode used would seem to yield the truest answer to the experimental inquiry. Sandstones, of course, having no polish, give no difference of result from this cause. It must also be remembered that the general tables seek as nearly as possible to give the average strength of the average stone from any particular quarry, while the "Sundry special experiments," having been made with carefully picked stones, will give higher results from that cause. There may be some exception to the last remark in the East Chester marble, but, if so, that is believed to be the only one.

Each specimen of all the kinds was carefully prepared by an expert stone-cutter, and the bed-side marked. These were then placed upon a table near the hydrostatic-press, used in such a manner as to mix them completely, and so prevent any inadvertent choice being made when they were picked up. They were there examined, squared, measured, and calipered, and then tested on bed or edge, under steel, wood, lead, or leather, as the routine prescribed. When placed in the press, each specimen was carefully centered to the axial line of pressure, and the power applied neither fast nor slow, but steadily. The records were not attempted to be made exact within 500 pounds—equal to 125 pounds per square inch on 2-inch beds and over. On smaller specimens than 1-inch cubes 100 pounds was made the limit of error.

The weight of the movable parts of the press, with its attendant friction and the pump-stroke—about 800 pounds in all—is to be subtracted from the records in the general tables, or 200 pounds per square inch. The subject of friction is discussed under the head of "Testing the press and gauges."

GAUGES.

The press is supplied with two gauges, one indicating the pressure up to 100,000 pounds; the other to only 5,000 pounds. Both are connected by pipes with the lower end of the cylinder of the ram. Both gauges may be used simultaneously until the capacity of the 5,000-pound gauge is exhausted, when its connection with the cylinder is shut off by a little valve worked by a hand-wheel. Generally, in testing stones, the lighter gauge is not used.

To check the working of the 100,000-pound gauge next to the press, another gauge of similar capacity was employed as a test-gauge. It is attached to the connecting-pipe, near to the pump. These gauges were manufactured in the city of New York, on a modified arrangement of Bourdon's principle.

THE BREAKAGE OF STONE.

The diagram accompanying this report shows sketches of eight samples of stone. The first one, named homogeneous stone, is imaginary, and represents the general form of breakage of many sandstones and saccharine marbles. The separate pieces shown are such as are usually picked up after breakage, although with other varieties of stone they are generally more angular. The other sketches of stone represent samples actually tested and broken. The numbers given with each of them correspond with those in the tables. The position of the cube when tested is also stated, whether it was placed on "bed" or on "edge."

Considering the infinitely-varied composition and character of all kinds of rock, it may be said that no material is less calculated to permit the establishment of special laws by a general form of breakage. It may be safely assumed, however, that more numerous and extended experiments, carefully and patiently conducted, will ultimately lead to the development of certain general laws relating to the behavior of stones under pressure, a knowledge of which will be most useful to the engineer and builder.

Homogeneous stones seem, in most cases, to break in the following manner, (see Plate I:) The forms of fragments *a* and *b* are approximately either conical or pyramidal, according as the stone is friable and of obviously granular structure, like sandstone and a few kinds of marble and granite, or compact, such as the true limestones and most marbles and granites. The more or less disk-shaped pieces *c* and *d* are detached from the sides of the cube with a sort of explosion, flying off in a more or less intact condition. In *e* and *f*, the stone is generally found crushed and ground to powder by the attrition of the larger fragments. Of course, this general result is modified by the nature and quality of the grain in the stone, and those other causes of irregularity which leave no two cubes of the same strength and condition, although they may have been cut directly apart from each other.

This form of breakage occurs also in non-homogeneous stones broken on bed; but it must be remembered that here the modification must be taken into account which "grain" produces as against homogeneity, rendering the object liable to split in rectangular fragments. This frequently lengthens the cone or pyramid in stones on bed, and causes those set on edge to actually split in rectangular disks; the style of splitting being, of course, irregularly modified for different specimens. Sand-cracks, &c., in stones have also their influence in directing the pressure; even the difficulty of determining the bed in some stones, after being cut, may be a source of errors.

SPECIFIC GRAVITY.

The stones whose resistance to crushing-pressure had been tested were also experimented upon in relation to their specific gravity. In the course of these investigations, it was sometimes necessary to be content with rather small fragments of stone, of not more than 15 to 18 pennyweight; but generally they weighed from one to two ounces.

On commencing this part of the work, some doubt was felt in regard to the best means of obtaining the correct displacement of porous stones; and all stones are more or less porous. It appeared evident that in weighing the stone first in air and then in water an error would be committed by saturation. The first idea, to give the stone a coating of thin varnish, was abandoned, because, although the pellicle would be thin, yet no means could be taken to know precisely what its thickness was, or what it amounted to in its effects. The second idea, to soak the stone in very fluid resin, the pellicle to be washed from the surface before dry, was given up, because it was desirable to preserve the specimens intact for experiments on freezing and other tests.

The plan finally adopted was, first, to remove from the stone all loose particles, and round off all sharp corners and edges, bringing it, in fact, practically to that condition commonly known as water-worn. It was then carefully weighed in air, immersed in water, and allowed to remain there until all bubbling had ceased, and its weight taken. It was then taken out of the water and weighed again, in its saturated condition, with the precaution of previously denuding the stone of superabundant water, by being compressed lightly in bibulous paper. The specific gravity is now found by dividing the weight of the stone, when perfectly dry, by its weight in the air after having been saturated, *minus* its weight in water.

This may also be expressed by the formula—

$$\text{Specific gravity} = \frac{W}{W_{\prime\prime} - W_{\prime}},$$

W representing weight of dry stone in air; $W_{\prime\prime}$ representing weight of saturated stone in air; $W_{\prime}$ representing weight of stone immersed in water.

In determining the specific gravity of stone, the weight of water was assumed to be 62½ pounds per cubic foot.

RATIO OF ABSORPTION.

The term "ratio of absorption" simply expresses the weight of water absorbed by the stone as compared with the weight of the dry stone; that is, if the stone when dry weighs 300 units, and the column of "ratio of absorption" shows the fraction $\frac{1}{300}$, it means that, by immersion in water, the stone will absorb 1 unit of it, weighing 301 units immediately after its removal from the water.

The method adopted for ascertaining the specific weight of stone furnished at the same time the means to determine the "ratio of absorption." The weight of the saturated stone minus the weight of the dry stone gives, as a result, the amount of water absorbed. This might, perhaps, more correctly be called the "avidity of absorption," since it was limited to the period of bubbling. Some few stones, having been kept immersed in water for several consecutive days, showed a slight increase in weight.

Since the capacity of a stone to absorb water has much influence on its durability, even during the warm season, and far more so in cold weather, the addition to the tables of this column was deemed advisable.

TESTING THE PRESS AND GAUGES.

It was deemed essential that the accuracy of the gauge records should be verified, and that the law under which friction was developed under varying pressure should be ascertained for the instruments actually used in testing the several kinds of stone, viz, Hoe's hydrostatic press, and Willing & Co.'s gauges.

Two gauges were used. One of them, of 500 pounds capacity, was extremely sensitive; so much so that besides other useful results, it accurately indicated the power used in lifting and working the unloaded ram, leaving only the efficient power and friction to be accounted for or measured. The other and larger gauge has a capacity of 100,000 pounds.

From careful experiments made by Mr. J. Hicks, civil engineer, of Bolton, England, on rams of 4-inch and 8-inch diameter, it appears that the friction of a 4½-inch ram—the one used in these trials—is about nine-tenths of 1 per cent. of the total pressure.

Assuming the law of the increase of friction to have been definitely ascertained by these experiments for hydraulic presses generally, it was thought best to make some special trials with the one in use. These were several times repeated with approximately corresponding results.

They were conducted in the following manner: It had been repeatedly noticed that small cubes of Michigan pine, when placed in the press and crushed against the grain, gave very uniform results. One-inch cubes, for instance, cut from the same piece side by side, crushed suddenly at from 5,800 to 6,000 pounds pressure. An average obtained with 1-inch cubes of pine crushed separately was thus established.

It was further ascertained by trials that sets of 2, 3, 5, 10, 15, 16, or 18 1-inch cubes of the same material, placed in the press in succession, the cubes in each case being set side by side, though not within lateral supporting-distance of each other, gave proportional results—that is, the aggregate crushing pressure divided by the number of cubes, gave the average crushing strength obtained with the single cube, within a reasonable limiting error of, say, 500 pounds for large numbers. All the cubes in each set crushed suddenly and together. Several repetitions of this experiment gave similar results. It was also tried with 2-inch and with 3-inch cubes, the aggregate crushing resistance—friction, of course, included—being always proportional to the number of cubes simultaneously crushed. The results of the more exact experiments of Mr. Hicks were therefore corroborated, that the resistance from friction must have been a constant percentage of the power employed, and not, as has been sometimes supposed, a differential increase. Indeed, this last-named hypothesis could not possibly obtain under the known laws of friction unless abrasion should set in between the lubricated leather packing and the copper lining at between 1 pound and 6,000 pounds pressure per square inch. These were examined after a year's time, during which the entire power of the ram up to 100,000 pounds—equal to 6.290 pounds per square inch—had been repeatedly used. The leather was found to be natural and the copper glazed. Abrasion therefore had not taken place.

There appears to be a singular and unfounded prejudice against the use of gauges for recording pressures, due apparently to the fact that several having proved incorrect, when properly tested, the results have been more or less widely advertised; while the true instruments, constituting a very large majority of those in actual use, have remained unnoticed. It is unnecessary to say the same rule would banish the yard-stick and the pound-weight from existence, the first being often too short, and the latter too light.

The three principal kinds of gauges are the *spiral-spring* gauge, the *diaphragm-spring* gauge, and the one used in all the experiments and tests herein recorded, known as the *tubular-spring* gauge. Its essential and characteristic feature is the tubular spring made of fine cast-steel, carefully bored, bent, tempered, and tested. The bending of course changes its original circular section to an elliptical one. As the fluid is forced into this, the greater pressure in the direction of the minor axis tends to change its sectional form toward the circle, as the figure of greatest capacity, which of course it can never reach until it becomes straight as at first, but which it approaches as the pressure increases, growing straighter at the same time. It is this straightening of the spring which works the gearing and revolves the index-hands.

The fact that this simple instrument can be made to register correctly upon a graduated dial, is full proof of the great delicacy of which it is capable. It has certain advantages over the beam-scale for large pressures in this, that while the beam may be very correctly graduated for any ratio, say 1 to 100, and be very perfect for comparatively low pressures, yet it depends upon knife-edges, which, when we have raised our power, say to 100,000 pounds, or higher, may begin to abrade, to sink into the plates supporting them, and to obtain another and an unknown law of friction. Therefore, although the ratio of 1 to 100, or that of any given beam, may be very perfect within certain limits of power, we cannot rely upon preserving that ratio, or rather we may be quite certain that it is not preserved when those limits are exceeded. The worst is, that we do not know to what extent the ratio of the beam is incorrect in recording high pressure.

The gauge has all the pressure put upon it, when tested for accuracy, that it will ever have to bear. It requires simply to be tested up to its maximum per square inch, seldom equal to 8,000 pounds. Then, if the ram is never worked at over 8,000 pounds per square inch, which the safety-valve should insure for the safety of the cylinder, there comes no more pressure upon the gauge from a cylinder of 300 square inches than from one of 0.03 of a square inch.

The ram used in these experiments having only 15.9 square inches area and 100,000 pounds power, the maximum pressure per square inch is 6,290 pounds, nearly, or 1,572½ pounds to the one-fourth of a square inch. The accuracy of the gauge-scale may therefore be thoroughly verified with a beam-scale known to weigh correctly up to 1,572½ pounds and a hydraulic press having a cylinder of one-fourth of an inch sectional area. Of course the same gauge could be taken from the 15.9 square inch cylinder and placed upon a 15.9 square inch cylinder, and the gauge-records multiplied by 10 would give the true power used, the actual pressure on the gauge when weighing 1,000,000 pounds remaining precisely the same as when weighing 100,000 pounds on the smaller ram; that is, 6,290 pounds per square inch. However, any small error in the ratio of areas between the quarter-inch cylinder and the 15.9-inch cylinder would also be multiplied by 10. To show how this might be reduced by scientific application to indefinitely small quantities is foreign to the requirements of this paper.

SUNDRY SPECIAL EXPERIMENTS

Showing differences resulting from the use of various surfaces of pressure, including steel, wood, lead, and leather ; differences in the compressive strength per square inch in different-sized cubes ; and of prisms of various heights in relation to breadth of bed.

The first of these commenced with trials of the different results to be obtained in amount and mode of fracture between stones of same kind, and from the same block, all 2-inch cubes in magnitude, with different pressing surfaces. Hardened-steel faces, wooden cushion-blocks, about ¼ of an inch thick, cushions of lead, about $\frac{1}{20}$ of an inch thick, and afterward thin lace-leather, were introduced into the comparison.

The specimens, as before observed, were taken for each experiment, from the same block, approximately yielding just the number wanted; were then most carefully brought to parallel beds by being ground in an iron frame upon a stone plane-table with sand and stone-dust, and were then truly squared. Their surfaces, especially the beds, were on the borders of polish, as nearly as the character of the stone allowed. When set out upon the table for use, they were carefully mixed up, calipered, squared, and measured, and the trial commencing with steel, was alternated regularly, the second stone being broken with wood, the third with lead, and, in the second part of this series of experiments, the fourth with leather. This plan was varied on a few occasions only, when an evident flaw was observed, and the results omitted from the table.

The instrument used to give security to the direction of the pressures was of the following description: (See Fig. 1.)

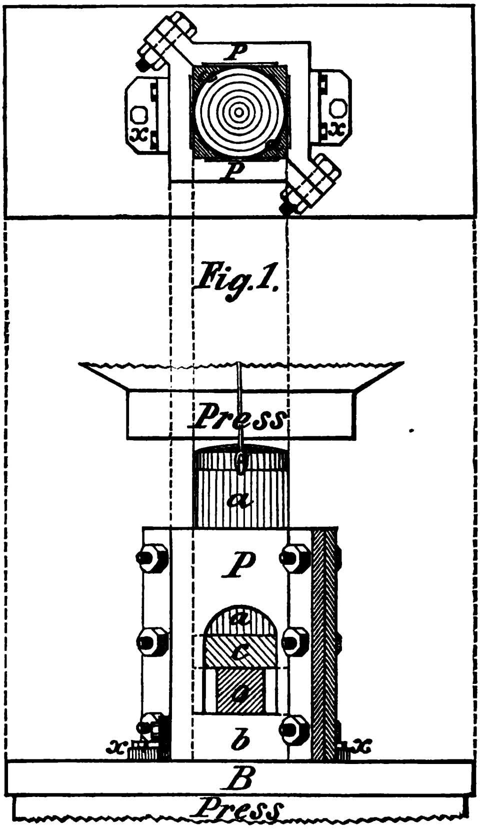


Fig. 1.

P, is a cast-iron frame 1 inch thick; *B*, a 1½-inch cast-iron plate, to which it is fastened by lugs *xx*; *aa*, cast-iron mandrel with steel plate *c*, 1½ inches thick, secured to mandrel by 1½-inch steel screw wrought on back of plate; *b*, steel disk, 2 inches thick, set into same guides in which mandrel works. The mandrel and disk have 4-inch by 4-inch square faces, exactly parallel to each other and perpendicular to guides. All the steel was hardened to straw color and then worked true. The mandrel is secured to the top beam of the press by wire cordage, the weight of the frame bringing that down easily after each breakage. The object O is placed truly under the center of the mandrel, through one of the four arched apertures in the frame, and the frame raised again by the pump, the stone being broken between the steel face *c* of the mandrel, and the steel disk *b*.

The top of the mandrel is segmental, so as to create no resistance to the true action of the guides, and a balk of wood, 4 inches by 4 inches by ½ inch, is laid upon this segmental top. This became hard and convex, but lasted throughout all the experiments.

The phenomena of breakage by the steel and wood were nearly the same; a tendency in steel to make one pyramid of from 50° to 60° angle at base, rather than two of 45° each, was occasionally suggested, but not sufficiently so to indicate a law. In both cases the form seemed to be of pyramids forcing out end pieces, and usually breaking them up. The end pieces from the wood were, as far as observed, slightly more prismoidal, and from the steel, more wedge-shaped. It is impossible to speak with certainty, however, on this point; the frame *P*, in both cases, confining the fragments, and thus securing much greater destruction, by preventing their escape from the reaction of the press, than when they were free to fly off at the moment of rupture.

With the lead, and subsequently with the leather, the phenomena were entirely different.

A dull thud, instead of a pistol-like report, and sometimes only the mere recoil of the gauge-needle, recorded the destruction—a destruction indeed which was complete. To the observing eye, vertical cracks burst instantaneously upon the sides of the specimen, about one-fourth of an inch apart, and all its cohesion was gone at once. Examination showed the fragments to be prismatic, with the greater dimensions parallel with the direction of the pressure, and with an unusual quantity of stone-dust intermixed. To be sure the central portions tended slightly to the pyramidal form, but the fragments from the steel and wood trials are solid like the original stone, having little appearance of internal injury, but only of having been severed from each other forcibly. Those, on the contrary, from the lead and leather trials, appear to have been riven to their utmost recesses, and crumble between the fingers like wood-cinder, having been apparently cleaved everywhere and in every direction in a manner, however, suggesting general parallelism with the line of pressure at the initial moment of rupture. The very constitution of the rock is shattered when crushed in this manner.

And it is not that the lead or leather appears to spread much. They do not spread in all directions so much as the wood does in one. The phenomena seems to be this: that while one side is being made smooth by the steel plates the other appears to be driven into the microscopic interstices of the rock, intruding by flowage—after the manner described of metals in Trescas' experiments—then opening and splitting it by crowding pressures, and thus from each end driving myriads of minute wedges into the rock, while the normal pressure causes a powerful tendency to open in the middle. (See Fig. 2.)

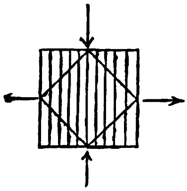


Fig. 2.

Lace-leather is of an extremely close texture, something like oil-soaked rawhide, and retains in a great degree, like lead, the characteristic lines of the rock surface stamped upon it. Ordinary fibrous leather might have a different action.

This course of special experiment was conducted in three stages. Stones of a well-known stable character, selected either from previous acquaintance or from knowledge otherwise derived, were used. In the first, Mill Stone Point granite was used, a stone of considerable hardness without brittleness, of weathering durability, and, from its clear fracture, evidently possessed of good tensile strength, even in proportion to its compressive resistance. In the second stage, East Chester marble was employed, and in the third, Berea sandstone of the blue-gray color.

TABLE III.

Table III shows very plainly the quantitative relations which pressing surfaces of steel, wood, lead, and leather bear to each other in the breakage of these several rocks.

Now as the stones above mentioned were all relatively high in their respective resistances, and as it was evident that a very weak stone, crushing below the pressure per square inch at which wood, lead, or leather could exert idiosyncrasies different from those of steel, would yield indifferently to either, it was naturally supposed that the differences observed would rather converge as the compressive resistances of rocks decreased.

The fact, however, that the characteristic breakage and the observed phenomena of yielding under wood were different from those observed with leather or lead, while all concurred in departing more or less from the quantitative results obtained with steel, suggested a continuation of the experiments so as to include rocks of the same kinds in name but of different characteristic. Directions were therefore given to obtain granite similar to that used as the inside lining of the capitol at Albany, and a marble similar to the Vermont marble, both of which were well known from prior experiments. These are both solid stones of fine grain, which take an excellent and beautiful surface, but are both, relatively to their kind, and certainly as compared respectively with the Mill Stone Point granite and East Chester marble, of a friable character. This may even be observed by attrition with the thumb-nail upon a fresh fracture, and they evidently possess less tensile, and therefore less beam strength, than the average rocks of their kind. The first, though well knit together, is micaceous in small spangles, the other granular like white sugar.

These stones were then tried under precisely the same circumstances as those foregoing, with this exception, that several of them cracked before breakage—an occurrence which did not happen to the others—and were, therefore, excluded from the record.

TABLE III A.

The result of these experiments shows a divergence instead of a convergence in relative results, and as the last-named, or softer, granite gave under steel, whêre its compressive power may be supposed to be tested, the same results as the first, it became suggestive that it was not the property of softness alone which had quantitatively changed the results between the two, under the rigid steel and the spreading wood. It was well, however, to test this by other experiments. There happened to be on hand a block of soft Sebastopol limestone or chalk, taken from the ruins of the Malakoff, which was, at least, soft enough to suit the purpose. There were also on hand three 1½-inch cubes of a soft drab sandstone, and two specimens of sandstone from Massillon, Ohio. The first, or the chalk, crushes at about 1,000 pounds per square inch; the drab sandstone at about 4,000 pounds; and the Massillon sandstone at from 6,000 to 8,000 pounds.

Now if the softest of these stones gave the same results with steel, wood, lead, and leather, there could be little doubt that, so far as softness was concerned, the results would not be divergent.

A glance at Table III, A, will show that this is the case both with the chalk crushing at 1,000 pounds and the drab sandstone crushing at 4,000 pounds per square inch; the former giving a uniform percentage of 100 for steel, wood, lead, and leather, and the latter the same for steel, wood, and lead, the trial with leather having been omitted.

For the Massillon sandstone of the softest kind, crushing at about 6,000 pounds per square inch with steel, we find the wood cushions giving results about 20 per cent. higher than those of steel. One of the four results obtained with steel plates, however, shows so much discrepancy, compared with the three others, that it may be rejected, and we may safely put steel and wood at 100 ± per cent. each, lead at 90 per cent., and leather at 60 per cent.

Here the difference between the lead and leather evidently results from their relative softness, the lead probably beginning to flow at a pressure of about 5,400 pounds per square inch, while the leather probably begins at near 3,600 pounds per square inch. For the Massillon sandstone, crushing at 8,000 pounds per square inch, with steel, we again find only a slight difference between steel and wood cushions; but here appears to be another boundary, where the lead plates again take their position at 85 per cent., (or half-way toward the normal amount at high pressure, 65 per cent.,) which seems to commence at about 7,500 pounds per square inch, from whence it remains constant to at least 25,000 pounds per square inch for steel, or 16,250 pounds per square inch for the lead itself.

With Berea sandstone, Table III, we have the lowest results of the general average, steel giving 11,000 pounds per square inch crushing strength; wood, 10,000 pounds; lead, 7,500 pounds; and leather, 6,700 pounds; the percentage being as follows: steel, 100; wood, 91; lead, 65; and leather, 60.

Down to these points, then, our deduced averages, taken from the table, are sufficiently accurate for practical work; and below these points, that is, among the softer and weaker stones, the peculiarities of the pressing surfaces are not developed, and we get about the same results, whether we use steel, wood, lead, or leather.

It seems probable that the real cause of the divergent results obtained with the stronger and harder stones lies in the relations existing between their tensile and compressive resistances, and that the law under which those divergencies are disclosed will be expressed in functions of those relations.

The properties of tensile strength, compressive strength, and hardness, though common to all varieties of rock, vary in their relations to each other among the different kinds within measurable and sometimes within comparatively wide limits.

It is practically known among builders that a stone may be very hard and yet be very inferior to another which is softer, if it is to be placed where any tensile or beam strain will come upon it. The subject will be further discussed in this connection after all the experiments, others of which bear some relation to it, shall have been described.

TABLE IV.

Other experiments were made, and appear in Table IV, regarding the difference between the resisting powers of stone—in this instance confined to one kind—at one-half, once, twice, and three times the bed-diameter in height. These, curiously enough, conform precisely to the specific experiments made by Mr. Hodgkinson, and probably point to his further correctness in cases where the width of base is still less in proportion to the height. It will be obvious, however, from the number and completeness of these trials, that the general principle which he seeks to establish, namely, that the compressive resistance of rectangular blocks, when crushed between plates by a vertical force, is proportional to the horizontal area of the blocks, is entirely incorrect when the height is near or less than the bed-diameter. Results in this connection are more elaborately worked out in the two sets of experiments on the breakage of different-sized cubes with which this section concludes.

With blocks having different relative heights the difference in the manner of breakage is very observable.

Those in which the height is one-half the width of bed are in all cases simply crushed to powder under steel and wood, and are more inclined to split in fine splinters, which easily become powder under lead and leather.

Cubes break, as has been before described, into solid fragments under steel and wood, and under lead and leather split into as nearly a fibrous condition as stone can sustain a fibrous form.

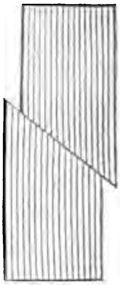


Fig. 3.

Stones having a greater height than width of bed are partly split into large prisms by wood and steel, but more characteristically are broken across their heights in an oblique plane, precisely as wood yields when, having greater height than diameter, it is pressed in a direction parallel with the fiber, as shown in Fig. 3. None of these latter were tried with either lead or leather.

A more detailed description and discussion of Table IV will come into subsequent parts of this report, and therefore, to avoid a repetition of words, they are merely passed over here with brief notice.

TABLE V.

The experiments recorded in Table V were made on beams of stone of 2 inches cross-section and 6 inches long, broken on supports 2½ inches apart; the bed being upon a long side, and receiving the pressure normally. They were not quite satisfactory, because the first record was only approximately deduced, and because there were no specimens of the more fragile Vermont marble broken. These beams had partially flexible supports under them, made of soft pine, extending from the end 1¾ inches toward the center. A wrought-iron cylindrical rod, ½ inch in diameter, was laid across the top center, and the power applied to it. The results were as follows: Mill Stone Point granite, 4,000 to 4,500; East Chester marble, 4,000 to 4,200; Keene (N. H.) granite, 3,300.

From the known fragility of the Vermont marble in comparison, it could not have stood over 2,500, or, at most, 3,000, pounds. Accepting the larger number hypothetically, we should have Mill Stone Point granite, 100; East Chester marble, 100; Keene (N. H.) granite, 77; Vermont marble, 75, as the relative beam strength of the stones compressed with steel, wood, lead, and partially with leather, in the first part of these discussions.

TABLE VI.

The special experiments, Table III, with the different mediums for communicating the pressure—viz, steel, wood, lead, and leather—were made with stones in a fairly-polished condition, when polishable stones like granite and marble were used. The sandstones were rubbed to a fine smooth surface. Now, inasmuch as the general tables were prepared with stones that were not polished, and many of which were incapable of receiving a polish, though all were carefully dressed to a smooth and even surface, and crushed between disks of pine wood, some variations of results were to be apprehended from differences in the condition of the surfaces of the cubes to which the power was applied, even though the same compressing medium was employed.

Some closing trials, recorded in Table VI, were therefore made, in order to obtain requisite data for making a connection between the special results and those recorded in the general tables. It seemed to be fair in this case to use as many different kinds of stone as practicable, rather than to divide the same number of experiments among several specimens of the same kind; because the general tables, comprising carefully-selected average stones, rather than fine specimens, are really the basis upon which all the others depend; and, as the general tables afford us numbers of trials already made with practical beds, which could be paralleled with polished stones of the same kind, it was concluded to use them. One difficulty, however, remained: specimens could only be replaced, as regards certain kinds of eastern rock, which were at the head of the list, and several of these had, in the general experiments, cracked long before breakage, and thus broken at a disadvantage. The difficulty was obviated—nearly so, at least—in the following manner: extra fine specimens obtained for the second or special trial were carefully polished, all breakages from cracking were thrown out, and these were compared only with the best specimens of similar kinds in the general table. The difference appears to be about 25 per cent. in favor of polished surfaces, but is probably a little less. Sandstone, being incapable of polish, and consequently always similar in surface, gave in all the trials no appreciable differences.

One object of these experiments being to connect together, as closely as possible, all the various trials that have been made by experimenters, in which various substances have been used as pressing-surfaces, it was also necessary to add another series, on the strength per square inch of different-sized cubes; this selection of form being made because almost all experiments had been conducted with cubes, whatever the size used; and because reason, experience, and precedent seemed to concur in the advantage of that selection.

Among the experiments of Mr. Hodgkinson which are of peculiar interest are those relating to the question of a changing strength, as the bed-surface of any substance increased in area. For this he used teak-wood in cylinders ½ inch, 1 inch, and 2 inches diameter, and in each case twice the diameter in height. It will be recollected that he thus obtained results showing the ratios of strength to be 1 : 4 : 16 : or, in other words, the same resistance per square inch of bed-area.

Now, on the contrary, 1-inch, 2-inch, and 3-inch cubes of Michigan pine, crushed against the ends of the fiber, during the course of these trials, gave a considerable increase in strength per square inch as the size of the cubes was increased. This test with pine was only intended to be preliminary to similar trials with stone, should the results seem to justify the necessary expense thereof, and is not of itself especially worthy of record. It only gave a direction to further experiments.

Referring to Tables II and IV, and taking them in connection, we find by the former that a 1-inch cube of bluish Berea sandstone, broken under steel, sustains 9,500 pounds, and that consequently four separate cubes of that size crushed side by side would just sustain four times as much, or 38,000 pounds. Yet, when in one piece, forming a slab 2 inches by 2 inches by 1 inch, or, so to speak, when they are connected together by their own substance, it actually sustains nearly 76,000 pounds, or twice as much as the set of four 1-inch cubes; and when the height is increased into the form of a 2-inch cube, it sustained nearly 50,000 pounds, or less than two-thirds as much as the slab, although one-third more than the set of four 1-inch cubes. When the height is further increased to twice the width of base, it sustains only 44,000 pounds, or fully one-tenth less than the 2-inch cubes.

The general cause of these differences is readily obtained from the course of the strains, which—if we suppose them for simplicity to act at an angle of 45° in the stone, and the material is known, under the same circumstances of crushing, to yield under a constant angle—do not produce results in the cube in the same manner that they do in the slab. (Figs. 4 and 5.)

The lines in the cube (Fig. 4) have a tendency to push out the material half-way up the sides at *a b*, while they are restrained in the slab

(Fig. 5) by the frictional resistance of the steel plates to the lateral motion of any parts of the specimen.

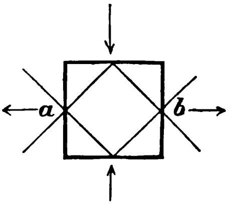


Fig. 4.

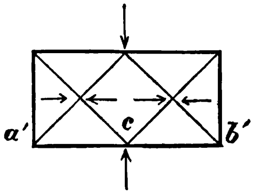


Fig. 5.

Now it is evident from the relations of hard slabs, broken by wood and steel, that these differences should be decreased with wood cushions by their yielding to the pressures *a′* and *b′*, resolved horizontally. This is also evident from the same table, because slabs and cubes of the same bed-area broken by steel give differences of 50 per cent., while the difference between slabs and cubes of the same bed-area, broken by wood, is only 5 per cent. And still further, we see that as we rise in the height of the prism broken by steel, so that the side-strain cannot be absorbed by the very rigid metal, the closer become the relations between prisms of different heights. At the same time the results obtained with wood and with steel cushions approach each other.

Could it have been foreseen in an early stage of these trials that the results, while fully corroborating those of other experiments so long as their methods were precisely copied, yet departed from them very widely by change in the form of the specimen, (so widely, indeed, as to be in practical opposition thereto,) they would have been carried much closer to exhaustion.

Nor are we debarred from a very close determination of the corresponding relations, when stone blocks of various forms are crushed between disks of wood. In Table I we find that a 1-inch cube of the yellowish-gray sandstone breaks at 7,000 pounds. Four of these placed side by side would therefore require 28,000 pounds to crush them. But one 2-inch cube breaks at nearly 36,000 pounds, and as the difference between a cube of this size, and a slab of the same bed but only half the height, both of the same kind of stone, though stronger, and both crushed under wood, is only 5 per cent., (Table IV,) we may place the 2-inch by 2-inch by 1-inch slab of yellowish-gray sandstone at 38,000 pounds compressive strength. The difference of resistence, therefore, between a set of four 1-inch cubes, crushed simultaneously side by side, and four 1-inch cubes, horizontally joined together by its own material, or, in other words, a slab 2 inches by 2 inches by 1 inch, is about 10,000 pounds, the slab being nearly one-third stronger.

Having thus proved that there is a difference, we will now proceed to estimate the phenomena of that difference, and then to show its quantitative relations. The following data are taken from Table IV:

Ratio of height to side or base of prism.	Dimensions of prism.	How broken.	Total pressure, pounds.	Pressure per square inch, pounds.
½	2 inches by 2 inches by 1 inch	Under steel	75, 888	18, 972
½	1½ inches by 1½ inches by ¾ inches	do	34, 643	15, 397
½	Difference per square inch			3, 575
1	2 inches by 2 inches by 2 inches	Under steel	49, 137	12, 284
1	1½ inches by 1½ inches by 1½ inches	do	25, 350	11, 266
1	Difference per square inch			1, 018
2	2 inches by 2 inches by 4 inches	Under steel	43, 980	10, 995
2	1½ inches by 1½ inches by 3 inches	do	*24, 000	10, 666
2	Difference per square inch			329

* Deduced from 1½-inch cube, and the 1½ inch by 1½ inch by 4 inch columns, Table IV.

The results teach us that slabs increase in resistance per square inch greatly as their surfaces are increased. That cubes increase somewhat more slowly, about one-third or one-fourth as much. That columns increase within limits which may be covered by the natural inaccuracies of experiment, certainly not more than one-fifth of the cubic increase, or one-tenth of that of the slabs.

Again we accord with the specific experiments of Mr. Hodgkinson, while we plainly contradict the law "of the equality of intensity for all areas of pressure," which he deduces therefrom, in so far as he claims it to be general.

From this result the following experiments, which conclude this connection, may now be discussed.

TABLES I AND II.

Berea sandstone from the same ledge and stratum, being comparatively a very uniform stone for a soft one, was selected for these trials. There appear to be three kinds of Berea stone: one a rather soft, yellowish-gray stone with orange bed-lines, probably containing hydrated sesquioxide of iron as a pigment. Another, drab-gray in color, rather harder, which was not used except in the general table, and which seems to run into the two others, and to be less uniform in strength than either of them. The third, a bluish-gray stone without bed-marks, harder than the others, and of much more compact texture.

The stones from the tests, of which the lower curve Plate II (Table I) was constructed, were broken with wooden cushion-blocks, one-sixteenth of an inch thick for the ½-inch cubes, and increasing by steps to a little over three-eighths of an inch for the 4-inch cube. By an accident all these were not taken from one block, though all were of the yellowish-gray variety of stone.

The stones which produced the upper curve, Plate II (Table II) were broken with steel plates, were all from the same block, and of the bluish variety, which, being strong, restricted the upper limit to 2¾-inch cubes, as the largest that the press would crush with safety.

The sides of the cubes, increased one-fourth of an inch at each step, are shown in inches on the abscissa or horizontal line X. The vertical lines Y show the crushing-pressures in pounds per square inch of bed-surface, that is, the total resistance of the cube in each case, divided by the number of square inches in one of its faces.

The form of the theoretical curve is that of a cubic parabola, with the equation

$$y = \sqrt[3]{x \times a}$$

in which a is the cube of the unit-strain, or the pressure in pounds on a 1-inch cube which crushes it. The results were worked out from the averages given by the first trials with wood-cushions; those afterward made with steel being carried on to contradict or corroborate them.

In the lower curve, a is the cube of 7,000 pounds, the force in round numbers required to crush a 1-inch cube of the yellowish stone under wood; and in the upper curve, a is the cube of 9,500 pounds, the force necessary to crush a 1-inch cube of the blue kind under steel.

The equation for the lower curve will therefore be,

$$y = 7000 \times \sqrt[3]{x}$$

and for the upper one,

$$y = 9500 \times \sqrt[3]{x}$$

x being the side of the cube expressed in inches, and y the pressure in pounds per square inch of bed-surface at the moment of crushing.

It will be observed that the lower curve, constructed on the experimental results given in Table I *a*, makes only an approximative running in relation to the theoretical curve constructed according to the calculated results of the same table. The upper curve almost coincides in seven average points with the calculated curve; one point—that given by the 2½-inch cube—indeed, considerably falls short of its computed position. An examination of Table II, however, shows that the 2½-inch cubes at this point broke with nearly the same absolute pressure as the preceding 2¼-inch cubes. We may conclude that these specimens came from a soft vein in the block, and that this discrepancy may be neglected in view of the close approximation of the other points.

While the co-efficients, 7,000 and 9,500, will of course be different for different kinds of stone, they will also vary more or less for each kind of stone, according to the nature of the cushions between which the cubes are crushed. But these data once given, the formula would seem to afford a ready means for estimating the probable resistance of various sizes of building-stone in the form of cubes.

It appears, then, that, at least within certain limits, the compressive resistance of cubes per square inch of surface under pressure increases in the ratio of the cube roots of the sides of the respective cubes expressed in inches. Thus it will be seen from Table I *a* that the actual resistance of a ½-inch cube, expressed per square inch, was about 6,080 pounds, (5,558 pounds by calculation.) Now, according to the formula, a cube of eight times the length of side of a ½-inch cube, in other words, a 4-inch cube, should be crushed under a pressure of $\sqrt[3]{3} \times 6,080$ pounds per square inch, or 12,160 pounds. Actually it was crushed by 11,720 pounds, the difference being only 1 per cent. The calculated pressure per square inch of a four-inch cube is 11,112 pounds, being likewise a difference of but little more than 1 per cent. from the observed pressure.

The conclusion is, that having ascertained from an average of several careful trials the crushing-resistance of a 1-inch cube, an 8-inch cube of the same kind and quality of stone, crushed between the same sort of cushions, should show twice as much resistance per square inch of surface pressed as the 1-inch cube; while to produce three times the unit-resistance per square inch, the cube must have sides of 27 inches. This conclusion was, however, not borne out by experiments made in the

Brooklyn navy-yard, referred to further on. The discrepancy might, perhaps, be largely accounted for by the want of uniformity of grain and texture in comparatively large blocks. It was subsequently ascertained that the accuracy of the testing-machine used was by no means assured. The results may, therefore, be set aside for the present.

In regard to the application of the formula above given, there will arise the question as to the relations which exist under it between a number of combined cubic inches and a single isolated cubic inch. The formula for the pressure on each square inch of bed being

$$y = \sqrt[3]{x \times a}$$

and the total bed-surface of a combined cube, having sides x inches in length, being x^2, the whole crushing-power acting on the cube will, therefore, be

$$x^2 \times \sqrt[3]{x \times a}$$

The pressure received by each of the individual cubic inches, of which we imagine the whole cube to be composed, considering that the whole mass contains a number of cubic inches represented by x^3, is, therefore, equal to—

$$\frac{x^2}{x^3} \times \sqrt[3]{x \times a} = \frac{\sqrt{x \times a}}{x} = \frac{y}{x}$$

This result shows that while the crushing-resistance per square inch of bed-surface increases as the size of the cube is augmented, each individual cubic inch of the whole mass decreases in its power of resistance. For instance, by examination of the computed values in Table I *a*, we find that the crushing-resistance of 1-inch, 2-inch, 3-inch, and 4-inch cubes per square inch are set down at 7,000, 8,820, 10,095, and 11,112 pounds, respectively. But the average crushing-resistance of each individual cubic inch of these same cubes will be in the rapidly descending ratio of 7,000, 4,410, 3,365, and 2,778 pounds.

In this connection some discussion might be entered into concerning the ratio existing between the actually destroyed portions and the solid fragments of the cubes, as shown in the sketch of "homogeneous stone," Plate I, but it is omitted on account of the length which this report has already attained.

From the curves it follows: *That if certain cubes of unit dimensions are built together, with cement equal to their own substance, into a cube of larger dimensions and of homogeneous strength, the resistance to compression per square inch of bed-surface increases as the half-ordinates of a cubic parabola.*

As before mentioned, it is doubtful whether this law continues into the ordinary dimensions of building-blocks, and experiments in Table IV, where columnar side-force is taken into consideration, suggest, even should it apply to large blocks, that where the height of the wall is twice as great as its smallest horizontal dimension, no increased strength would be conferred on the wall, even if the cohesion of the mortar to the stone and its tensile and compressive strength were equal, respectively, to the tensile and compressive strength of the stone itself, conditions which never obtain.

In practice, the law would apply only to the individual blocks, having a height not much, if any, greater than the width of bed; but whether these are of restricted sizes, and, if so, what the largest size is, beyond which the formula fails, has not yet been determined satisfactorily.

The large cubes to which reference has been made were crushed at the Brooklyn navy-yard, with a 2,000-ton press, in which was a gauge subsequently tested to our test-gauge. Five 11-inch cubes of Berea sandstone were crushed. Whether the action of these stones was anomalous from specific causes, or whether from general causes, the law of the increase of strength per square inch fails at a particular value of x, it is impossible to say positively without additional trials. But these large stones broke invariably by splitting vertically in large flakes or sheets, varying from 2 inches to $\frac{1}{4}$ of an inch in thickness, and quite regular over the greatest part of their surfaces of fracture, especially the thinner ones. It is by no means impossible that all rocks have, more or less, a series of joints, somewhat resembling slaty cleavage, along which they open more easily than in any other direction. As the thickness of these joints belongs to the material, and is not changed by the size of the specimen, it follows, plausibly enough, from an examination of the annexed Fig. 6, and from the ordinary laws of the bending of columns and sheets transversely to the line of pressure, that the two sheets forming the small cube *a*, for example, having a height equal to only twice their width, will be crushed in combination rather than bend singly, while those of the large cube A, having a height equal to eleven times the width, will bend and separate rather than crush, and being thus bent and separated, will fly off consecutively from the block. This was the phenomenon displayed by the 11-inch cubes referred to. They crushed at somewhat less recorded resistance per square inch of bed than 2-inch cubes of the same stone. All the circumstances of their breakage, however, were very unfavorable, the accuracy of the testing machine, even, being extremely doubtful.

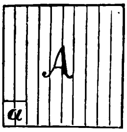


Fig. 6.

MODES OF EXPERIMENT DISCUSSED.

It was deemed proper, in my first report "on the compressive strength, specific gravity," &c., of various kinds of native building stone, submitted with my letter of July 30, 1874, to refrain from any positive enunciation of principle, for the simple reason that the experience gained in using disks of wood under and over the samples did not seem sufficient to justify a claim for special advantages in this departure from the usual methods of experiment. Indeed, there was a desire to elicit criticism upon what had been done, rather than to give prominence to the method of doing it. The question of the entire adequacy of this method for securing the object in view, and the reasons for adopting it, will be discussed as briefly as possible in this report. Not that this or any other manner of trial may be claimed to be the very best that can be devised; but only that, while admitting the necessity of obtaining the compressive strength of specimens for special and practical purposes, it may be also claimed that it is only by placing these specimens as nearly as possible under the exact circumstances which most occur in the combination of vertical and side strains, developed in actual masonry, that we can reach, or make much progress in, a solution of this useful problem.

No one can doubt the usefulness of experiments to obtain the crushing and tensile resistance of cast or wrought iron, or steel. But having these—the compressive and tensile strengths of cast iron, for instance—and combining them together to calculate the strength of a rectangular beam, we should find on testing the beam that we had wasted a large amount of material, and that it was much stronger than the results obtained by calculation indicated. Besides, therefore, the abstract knowledge of crushing-strength which we possess, we must also, by some series of experiments, combine these and other relations so as to learn whether, as in the case of beams and columns, there may not be new forces born of the combination, an acquaintance with which would materially add to our constructive power.

Connected with our subject, and therefore of special interest, is the discussion made by Mr. Hodgkinson in regard to the breaking of short prisms for the purpose of finding the exact crushing-resistance of cast-iron. Discovering in his earlier examinations that when these were shorter than their sectional diameter they resisted to a far greater extent than the metal could do as used practically, he thenceforth ignored such tests, beyond the simple fact of their existence, and confined his trials to prisms having a height of one and one-half the diameter or more, *because there the material gave way by the same laws, and in the same manner, as it does when used to guard human life, or secure valuable property.* In these trials he first discovered the angular breakage of material, and the law of constant direction, under the same conditions.

In making experiments on stone, it would, from the different nature and uses of the material, be evidently improper to follow blindly the modes used for cast iron. Here are no flanged girders or hollow columns to form culminating points of inquiry. Yet in principle we have the same necessity for reasoning directly toward the end to be ultimately attained, to watch carefully the character of the material, its mode or modes of yielding, the uses to which it is daily put, the peculiar stresses and strains which come upon it, and all this, not as an individual stone which our curiosity has induced us to investigate, but as the integral part of some vast natural structure taken down little by little, and transformed into smaller artificial edifices.

In regarding the idea of a crushing-force, the mind is too easily led to conceptions of vertical lines of strain, reaching directly from the weight at the top to the foundation at the bottom. It need hardly be said to engineers that such strains have existence only in the pages of mathematical applications, and could only be possible under the hypothesis of a film of material only $\frac{1}{5000000000}$ of an inch, or one molecule thick. So soon as another film is superadded, oblique arrangements of molecule and strain would intervene under pressure, and tangential stresses would be developed. If this were not true, there would be no such phenomena as angular breakage, spreading under weight, nor any need for bond on masonry, but blocks of stone, or brick, or any materials, piled vertically one upon another, would, under a destructive load, be gradually compressed into a smaller volume, *within the limits of their original horizontal dimensions.*

Thus in crushing an individual specimen, the principal lines of strain may be symbolized by the lines AB, BD, and AC, CD of the annexed figure (7.) A, being the crushing-force, D the resistance, and B and C the side-pressures. The angle of 45° is used only for simplicity, and because it is the maximum. Now, these strains have a tendency to push out the material at B and C, and cause either spreading or angular breakage, according as the substance is soft and cohesive or hard, granular, and brittle, while the resistance is at the same time increased or decreased by the rigidity, or yielding, or pushing of the foreign surfaces which press

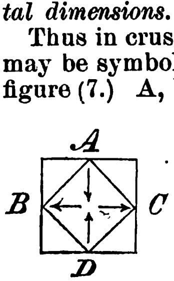


Fig. 7.

upon the object on the top and bottom planes at A and D. The nature of these surfaces, then, becomes a matter of great moment, as does also the height of the specimen in relation to its diameter, because each material has different uses in the arts, and because we know that the lines of strain have constant angles for each kind of material—depending to some extent, no doubt, on molecular arrangement—when crushed under the same circumstances.

In good masonry, in which the strength of the structure depends upon material and bond, stones should never be used of greater height than the breadth of the bed. Our experiments, then, unless we should purposely test for columnal strength, would not be made on objects over a cube in height. But early experiments showed that the cube gave quite sufficient opportunity for the natural angular breakage of stone, and subsequent trials with homogeneous kinds proved that, while slabs less than a cube in height, pressed by unyielding surfaces, gave much greater resistance than cubes, those higher than the cube to the limit of nearly three times the width were but little if any decreased in resistance by increased altitude. The cube, therefore, was the form depended upon for specimens; a determination carried out with greater satisfaction from the knowledge that other experimenters with stone had, for perhaps other reasons, arrived at the same conclusion.

Probably the first idea which would strike the investigator would be to make the pressing-surfaces of the same kind of stone as the specimen to be tested. But this surface must not be continuous, because we never build (except when forming a detached column, where each course is a single block) by placing one stone directly upon the top of another. Necessarily, for the strength of the structure, we introduce what is called *bond;* we have therefore *headers* and *stretchers*, and over and under each stone there are usually one or two joints, free in dry masonry, or filled with adhesive mortar in most works.

So, to arrive at this point, each object would have to be built in with others of its kind, in imitation of usual structures, and we could then calculate the several strains, and estimate the various strengths of the component parts of our experimental structure by the stresses which should be determined for them. This would be an expensive mode, would be difficult to tabulate, and would probably have its attendant errors, to be eliminated with great toil. We have then only one course left; we must study the strains which shall come upon the stone in masonry, and approximate to them as closely as possible in our tests of the material.

In the general case, we must consider that stone blocks are employed for building purposes in the form of a wall, and that if such side-strains as we have mentioned as coming upon an individual block should also be similarly developed in the structure, it would, with exceptional cases, strain the stone seriously only in one line.

If a wall be built high over a lintel and the lintel be then removed, no matter in what manner the wall is bonded, if there be a close juxtaposition of parts, so that the vertical and side stresses may combine themselves into oblique resultants, the masonry above the opening will not fall away in vertical lines from the top of the wall to the jams which supported the lintel, as it would if only subjected to vertical stresses, but will arch itself over the aperture and support the superincumbent courses. The magnitude of the side-stress, then, might be computed from the profile of the parts remaining.

Again, the ordinary pier, such as those too commonly built upon our county-roads and sometimes upon railroads, when yielding by incapacity to uphold the weight placed upon it, gives way, as in Fig. 8. At the top and bottom the width of the opening is zero, but it widens in the middle of its length. It may occur in the center if the work is of nearly uniform character, or at relatively weak points where it is not; but the side-strain is always evident, the two sides of the pier being deflected horizontally where the greatest strain comes.

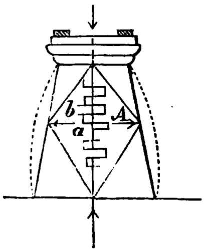


Fig. 8.

Now, this side-deflection is not produced as in an elastic beam mainly by the elongation of the outer line and the depression of the inner one, but is the result of a shearing strain alone, the slipping of the courses past each other; such an action, in short, as is sometimes corrected against in arch-thrust, and other important cases, by a vertical bond holding each two courses together. Such strains as that shown in the pier have torn stones asunder. In fact, stone is more likely to yield in this manner, where the work is well put together, than by crushing under vertical pressure.

For really good masonry, the danger may be approximately calculated. The stones in Fig. 8 have obviously slipped, because the "bond-grip" or "bight" was less than the tensile strength of the stone.

Take a good piece of granite masonry as an example, which shall be of first-class design, arrangement, and workmanship, and shall so far satisfy the general definition of good masonry, viz, "the smallest quantity to sustain a certain duty" that the *vertical stress* and the *compressive resistance* of the stone shall balance each other, and that the *side-strains* shall also balance the *tensile resistance*, and either of these the "bight" coming from *friction.*

Let us now assume that the granite block A, of Fig. 8, has been pulled by the side-strain from between the stones *a* and *b*; that the wall is built of cut stone, without mortar; that the transverse section of A is, for the sake of simplicity, 100 square inches; and that its bond between *a* and *b* has the same area. Now, taking granite at its highest tensile strength, say 3,000 pounds per square inch, and we have for the resistance to side-strain, by the tensile strength of the stone, 300,000 pounds. Taking the friction of stone on stone at 0.7, and the vertical force *which overloads the wall* at only 5,000 pounds per square inch, and we have 100 × 5,000 × 0.7 = 350,000 pounds. So the stone, if in a dry wall, would break rather than move. It is scarcely to be expected that good mortar or cement would decrease the strength of the bond, or that sandstone, which has nearly the same frictional resistance as granite and a tensile strength of less than 1,000 pounds per square inch, would give a better wall.

It is true that stones seldom give way in this manner, because good masonry seldom yields at all. Indeed, stone seldom yields by crushing. It is a cheap material, and the security is therefore kept high, but the benefit and object of experiment is to find the line of danger, and to know its true direction we must find its position at more than one point.

We have already chosen cubes for form, because they sufficiently secure the natural angular breakage which comes upon the single stone, and we have now, from the data exposed, to choose some surface of pressure to be applied to that cube, so as to impart to it, as nearly as possible quantitatively, the oblique pressures which each stone receives from its combination in the wall. Now, wood, which of all substances spreads its maximum in one direction, and but very little transversely thereto, would seem to serve our purpose. A few remarks on this point will suffice.

From Mechanics of Engineering, (Mahan's Mosely,) we have the following for the friction of different substances, at rest, which enter into our inquiry:

Co-efficient of friction of plane surfaces when they have been some time in contact.

Calcareous oölite stone upon same	0.74
Hard calcareous stone (muschelkalk) upon oölite	0.75
Brick upon calcareous oölite	0.67
Muschelkalk upon same	0.70
Calcareous oölite upon muschelkalk	0.75
Brick upon muschelkalk	0.67
Calcareous oölite upon calcareous oölite, coating of mortar	0.74
Smooth freestone upon same, dry	0.71
Smooth freestone upon same with fresh mortar	0.66
Hard, polished calcareous stone upon same	0.58
Hard, polished calcareous stone upon same with rough surfaces	0.78
Well-dressed granite upon rough granite	0.66
Well-dressed granite upon rough granite with fresh mortar	0.49
Oak upon calcareous stone, upon end of fiber	0.63
Oak upon muschelkalk, fibre flatwise	0.64
Pear-wood upon stone, (Wiesbach)	0.64

It is, of course, to be regretted that the friction of pine-wood upon stone generally could not be obtained. But the general course of the table leads us to take it as a near approximation to the result we seek, especially as the pine-wood is, under the pressure employed, as hard and tough as oak or pear-wood. Then, too, it may be thought by some that, as the wood acts by spreading, the friction of motion would be the true state to use, which would reduce the friction of wood on stone to 0.38 or 0.40, without materially altering that of stone on stone, either dry or mortared. But it must be borne in mind that this small motion of spreading against the grain of the wood, by searching the interstices of the stone, should rather increase the friction than otherwise, and is different from the motion of translation of the whole block, which would diminish the force by which the molecules of the two materials attach themselves to each other. But even if there should be a quantitative difference, within bounds, it must be allowed, even if it cannot be measured, because, of all substances, wood is the best, if not the only one available, for giving the side-pressure in one direction, which is what we set out to attain. We know that the surface of the wood contiguous to the stone has little or no motion, and that only the internal layers, especially the center ones, move with any freedom. The friction, therefore, while it will be somewhat less than that given in the above table, will not be as low as 0.38 or 0.40, the friction of motion.

Direct experiments in crushing blocks of different kind of stone between cushions of different material, viz, steel, wood, lead, and lace leather, were carefully made, in order to determine the ratio of resistance under the various conditions thus imposed. The steel plates were of sufficient thickness to be perfectly rigid under the greatest pressure to which they were subjected. Their effect is to hold the stone together by their frictional resistance to lateral spreading.

The wood—sheets of pine, a little over a fourth of an inch in thickness—spreads in one direction with comparative freedom, and thus throws a tensile strain on the block.

The sheets of lead and lace leather appear to be driven into the interstices of the stone, and, with slight spreading in all directions, to split it into vertical prisms as wood is split by wedges. (See sundry experiments.)

The first series of the experiments, Table III, was made on Millstone Point granite, East Chester marble, and blue Berea sandstone, all notably *tough* and first-class building-stones of their kind. The ratio obtained for the three taken together, omitting small fractions, was as follows, the leather being tried with the sandstone only:

Steel, 100; wood, 94; lead, 65; leather, 60.

The second series was made upon stones having nearly or quite as compact and close a texture on the ground-surface as the foregoing, but were more friable upon the surface of fracture and evidently possessed less cohesive and tensile strength. These were the Keene (N. H.) granite, used for the inside lining of the new State-house at Albany, and the Vermont marble, a clear, smooth, and delicate-looking stone. From these the following average ratio was obtained:

Steel, 100; wood, 82. × ; lead, 65.—; leather, 63.5.

This showed a material change for wood alone, which might occur either from the more or less tensile strengths, or have some connection with the hardness or softness of the stone. That it was not the latter must appear from the following discussion and corroborative experiments:

If it were the softness exclusively of the latter stones which produced this diminished result with wood-cushions, the difference would increase as the softness increases, but it is easy to perceive that a rock might be so soft that wood would not measurably spread, nor lead nor leather be made to "flow" under the pressure which would crush it, and, therefore, that steel, wood, lead, and leather would at some low point give the same result.

Fortunately, this could be reduced to direct experiment. On hand were some Sebastopol limestone, (*chalk*,) three cubes of a soft sandstone, and two sets of cubes of Massillon sandstone. These were all tested with the following results. (Table III A.)

Kind of stone.	Percentage with cushions of—				Remarks.
	Steel.	Wood.	Lead.	Leather.	
Sebastopol limestone or chalk ..	100	100	100	100	Mean of fourteen cubes, 2 inches by 2 inches by 2 inches.
Drab-colored sandstone	100	100	100	......	Mean of three 1¼ inch cubes.
Massillon sandstone, Ohio	100	110	90	59. 4	Mean of sixteen cubes, 2 inches by 2 inches by 2 inches.
Do	100	103	85	......	Mean of five cubes, 2 inches by 2 inches by 2 inches.

The above table shows about equal results with steel and wood, while the real crushing-resistance of the stones tested is much below that of the granites and marbles before mentioned.

It seems, then, that with stones of great hardness and toughness combined, steel and wood give approximately equal results; that with stones which, though hard, are yet deficient in toughness, the peculiar action of the wood-cushions spreading sideways, and thus exerting a strain requiring tensile resistance, causes the stone to be crushed at a lower figure than with steel, which latter, as already stated, tends to bind the stone together by its rigidity and frictional resistance to lateral pressure. With stones of considerably greater softness, the power of the stone to resist crushing is overcome before sufficient pressure has been developed to bring the action of the wood-fibers on the stone fairly into play.

Again, we may observe by experiments (Table IV) that when stone is in thinner slabs than cubes, greater strength is obtained to the amount of 50 per cent. under the pressure of steel. This is not so with wood, as may be observed in the same table, and engineers know that it is not so in actual work—that there is no remarked advantage nor disadvantage when the beds are true in each case.

Now this must be so, because, while the crushing-resistance is undoubtedly increased by thinness in the slab, the tensile resistance is decreased by the lessened number of square inches upon which it acts, and thus wood, compared with the experience of actual work, again asserts its true *quantitative relations.*

Wood has also the faculty of exposing the character of stone which suffers from "drys" or slaty cleavage, a fault which is disguised by lead and leather on account of their flowage, and by steel from its perfect rigidity.

The experiments, though far from being completed on this particular point, indicate a close relation between the beam or transverse strength of stone and its tensile strength; also, that a divergence between the compressive results obtained with steel and with wood cushions is accompanied by a corresponding divergence in transverse strength.

The beam strength of only two varieties of stone was satisfactorily tested, the beams being 2 inches by 2 inches in cross-section, broken on supports 2½ inches apart, with the following results, (Table V:)

East Chester, N. Y., marble broke at 4,000 to 4,200 pounds.

Keene, N. H., granite broke at 3,300 pounds.

The percentages of compressive resistance between steel and between wood cushions, for the same kinds of stone, were as follows, (Table III:)

East Chester marble, 100 for steel, 91 for wood.

Keene, N. H., granite, 100 for steel, 82.6 for wood.

This points to the existence of some law which cannot be enunciated or deduced without further investigation. It is true that stone is never, when it can be avoided, placed in positions where it is subjected to a transverse strain. Unequal settlement, however, which can rarely if ever be entirely prevented, is certain to produce it, and where great disturbance from such cause is to be apprehended, only stone possessing relatively great beam or transverse strength should be used.

TABLES OF SUNDRY SPECIAL EXPERIMENTS.

TABLE I.—*Showing the increase, in resistance, per square inch, of cubes of yellowish-grey Berea sandstone, as the size of the cube is increased. These were pressed upon by wooden cushion blocks, ranging from one-sixteenth to a little over three-eighths of an inch in thickness, as the cubes increased, and of the same bed dimensions as the stone. They were all broken on bed*

	¼″ cube.*	½″ cube.*	¾″ cube.*	1″ cube.	1¼″ cube.	1½″ cube.	1¾″ cube.
	260	1, 400	4, 000	6, 800	9, 200	17, 200	29, 200
	300	1, 500	3, 100	6, 950	13, 450	19, 200	33, 000
	330	1, 700	3, 200	6, 700	11, 200	16, 200	25, 800
	350	1, 500	3, 300	8, 200	10, 200	19, 200	30, 400
	300	1, 600	4, 000	7, 200	9, 700	19, 700	26, 200
	250	1, 500	3, 900	7, 200	10, 200	17, 000	26, 600
	300	1, 500	3, 500	6, 200	11, 900	20, 200	28, 200
	400	1, 500	....	7, 700	13, 200	19, 400	29, 800
	....	1, 500	....	5, 950	14, 200	17, 800	27, 400
	....	1, 500	....	....	....	19, 200	....
Total..........................	2, 490	15, 200	25, 000	62, 900	103, 250	185, 100	256, 600
Average	312	1, 520	3, 570	6, 990	11, 472	18, 510	28, 510
Square inch	4, 992	6, 080	6, 347	6, 990	7, 342	8, 226	9, 310

TABLE I.—*Increase, in resistance, per square inch, &c.*—Continued.

	2″ cube.	2¼″ cube.	2½″ cube.	2¾″ cube.	3″ cube.	4″ cube.
	32, 200	Cracked.	53, 200	75, 200	94, 200	187, 500
	32, 200	45, 200	50, 200	69, 200	90, 200	....
	25, 700	43, 200	52, 200	74, 200	89, 000	....
	42, 200	43, 200	66, 200	68, 200	....	....
	26, 800	50, 200	53, 200	70, 200	....	....
	43, 200	46, 200	57, 200	74, 200	....	....
	37, 700	47, 200	65, 200	69, 200	....	....
	43, 200	48, 200	50, 200	78, 200	....	....
	39, 200	Cracked.	50, 700	84, 200	....	....
	....	....	55, 200	81, 200	....	....
Total..........................	322, 400	323, 400	553, 500	744, 000	273, 400	187, 500
Average	35, 822	46, 200	55, 350	74, 400	91, 133	187, 500
Square inch	8, 955	9, 130	8, 856	9, 838	10, 125	11, 720

* It must be remembered that below a certain point per square inch, say seven or eight thousand pounds, the peculiar influence of wood becomes nothing; the strength of these is therefore relatively increased.

TABLE II.—*Showing the increase in resistance per square inch of cubes of blue Berea sandstone, as the size of the cube is increased. These were pressed upon by hardened-steel surfaces. They were all broken on bed.*

	1″ cube.	1¼″ cube.	1½″ cube.	1¾″ cube.	2″ cube.	2¼″ cube.	2½″ cube.	2¾″ cube.
	9, 400	15, 000	25, 000	34, 200	56, 800	69, 300	65, 800	94, 000
	12, 200	15, 800	28, 600	40, 600	38, 200	47, 800	65, 800	*100, 000
	10, 800	17, 400	19, 800	30, 000	50, 300	47, 800	52, 800	*100, 000
	11, 800	19, 800	(†)	38, 200	50, 200	53, 100	59, 300	*100, 000
	7, 800	16, 700	20, 600	25, 400	50, 200	79, 800	66, 800	91, 500
	10, 200	15, 240	28, 600	41, 800	30, 200	70, 800	72, 300	95, 000
	7, 800	15, 800	27, 800	23, 800	53, 800	65, 000	65, 800	*100, 000
	11, 100	15, 000	22, 200	40, 600	42, 800	70, 800	67, 800	....
	7, 800	16, 200	20, 600	39, 000	53, 800	59, 800	81, 800	....
	7, 800	13, 800	....	....	53, 800	69, 300	....	....
	7, 800	....	....	....	....	....	....	....
Total..........	104, 500	160, 740	193, 200	313, 600	480, 100	633, 500	598, 200	....
Average.......	9, 500	16, 074	24, 150	34, 844	48, 010	63, 350	66, 466	100, 000
Square inch ...	9, 500	10, 300	10, 730	11, 377	12, 000	12, 500	10, 635	13, 200

* Not broken. Average therefore deduced. † Cracked.

TABLES I*a* AND II*a*.—*Showing the calculated ordinates of cubic parabolas, deduced from the annexed formulas, compared with the actual averages obtained by breaking the stone, as shown more in detail in Tables I and II.*

TABLE I*a*.

x	Value of y deduced from calculation.	Value of y deduced from experiment.
¼ inch............	4, 410	4, 992
½ inch............	5, 558	6, 080
¾ inch............	6, 356	6, 347
1 inch.............	7, 000	6, 990
1¼ inches..........	7, 539	7, 342
1½ inches..........	8, 015	8, 226
1¾ inches..........	8, 435	9, 310
2 inches..........	8, 820	8, 955
2¼ inches..........	9, 170	9, 130
2½ inches..........	9, 499	8, 855
2¾ inches..........	9, 807	9, 838
3 inches..........	10, 095	10, 125
4 inches..........	11, 112	11, 720

$$y = \sqrt[3]{x}\ .7000$$

TABLE II*a*.

x	Value of y deduced from calculation.	Value of y deduced from experiment.
1 inch	9, 500	9, 500
1¼ inches	10, 231	10, 300
1½ inches	10, 877	10, 730
1¾ inches	11, 447	11, 377
2 inches	11, 970	12, 000
2¼ inches	12, 445	12, 500
2½ inches	12, 895	10, 635
2¾ inches	13, 309	13, 200

$$y = \sqrt[3]{x}\ .9500$$

TABLE III.—*Showing the resistances in total amount of 2-inch cubes of different kinds of stone, and of different qualities of the same kind of stone, under various surfaces of pressure. The beds of the granite and marble cubes were rubbed to the border of polish; those of sandstone were rubbed smooth.*

Kind of stone.	Steel.	Wood.	Lead.	Leather.
Granite, Millstone Point, Conn	93, 000	89, 000	68, 000	....
	91, 000	100, 000	66, 000	....
	96, 000	88, 000	60, 000	....
	91, 000	89, 000	57, 700	....
Average	92, 750	91, 500	62, 925	....
Percentage	100	98. 6	67. 8	....
Marble, East Chester, N. Y	80, 000	72, 500	47, 000	....
	*54, 000	73, 125	51, 000	....
	76, 000	*67, 000	48, 000	....
	96, 000	*68, 000	39, 000	....
Average	76, 500	70, 156	46, 250	....
Percentage	100	91. 7	62. 4	....
Sandstone, Berea, Ohio, (bluish-gray kind)	42, 600	42, 600	24, 360	26, 600
	54. 000	45, 000	31, 400	26, 800
	39, 480	37, 000	32, 200	27, 240
	41, 800	42, 600	33, 800	27, 000
	47, 240	38, 600	25, 800	27, 000
Average	45, 024	41, 160	29, 512	26, 928
Percentage	100	91. 4	65. 5	59. 8
Keene, N. H., granite, used in inside of new capitol Albany, N. Y.	100, 000	83, 000	55, 700	65, 700
	92, 000	84, 000	59, 500	60, 000
	96, 000	71, 000	58, 500	63, 000
Average	96, 000	79, 333	57, 900	62, 900
Percentage	100	82. 6	60. 3	65. 5
Vermont marble, Vt	56, 000	42, 600	37, 960	27, 200
	54, 300	43, 400	37, 650	31, 400
	51, 100	45, 000	39, 400	34, 600
	51, 100	42, 600	32, 200	37, 800
Average	53, 125	43, 400	36, 802	32, 750
Percentage	100	82	69. 4	61. 6

* The one under steel probably flawed; the two under wood slivered. Calculating the two would make the difference in the two columns about the same, so they were left as recorded on the gauge.

General average percentages from Table III.

Kind of stone.	Steel.	Wood.	Lead.	Leather.
First granite	100	98. 6	67. 8	....
Second granite	100	82. 6	60. 3	65. 5
First marble	100	91. 7	62. 4	....
Second marble	100	82. 0	69. 4	61. 6
First sandstone	100	91. 4	65. 5	59. 8
General average	100	89. 2	65. 1	62. 3
(Or omitting decimals) average	100	89. 0	65. 0	62. 0

TABLE III—A.

Kind of stone.	Steel.	Wood.	Lead.	Leather.
Limestone, (chalk,) Sebastopol, mean of 14 cubes 2″×2″×2″, all breaking at nearly same.	4, 300	4, 300	4, 300	4, 300
Percentage	100	100	100	100
Sandstone, drab, 3 cubes, 1½″ in all	9, 000	9, 000	9, 000	
Percentage	100	100	100	
Sandstone from Massillon, Ohio, 2-inch cubes	37, 000 31, 000	37, 000 33, 000	29, 000	
Average	34, 000	35, 000	29, 000	
Percentage	100	103	85	
Another and softer sandstone from Massillon, Ohio, 2-inch cubes.	29, 800 *17, 600 22, 600 21, 000	28, 444 29, 800 26, 766 22. 600	17, 800 23, 400 25, 080 21, 720	13, 000 14, 600 14, 600 16, 000
Average	22, 640	26, 901	22, 000	14, 550
Percentage	100	118. 8	97	64
*Omitting this result, and the percentage becomes	100	110	90	59. 4
Sebastopol limestone, in slabs 2″×2″×1″	4, 700 4, 500	4, 900 4, 500	5, 000 4, 700	4, 500 5, 000
Average	4, 600	4, 700	4, 850	4, 750
Percentage, (probable)	100	100	100	100

TABLE IV.—*Showing the resistance of prisms of blue Berea sandstone having different heights in relation to the width of bed, and broken under steel, wood, lead, and leather. The table is subdivided for convenience of reference in the discussion. The specimens were all taken from one block.*

	2″ × 2″ × 1″	2″ × 2″ × 2″	2″ × 2″ × 4″	1½″ × 1½″ × ¾″	1½″ × 1½″ × 1½″	1½″ × 1½″ × 4″
Broken between steel cushions	64, 000	58, 000	47, 000	32, 600	26, 200	21, 960
	83, 000	39, 400	35, 400	32, 200	29, 800	21, 000
	87, 500	51, 500	48, 200	30, 200	21, 000	24, 800
	75, 700	51, 400	42, 200	38, 840	21, 800	21, 800
	73, 800	51, 400	47, 100	33, 000	29, 800	22, 600
	65, 100	31, 400	....	40, 280	29, 000	....
	82, 100	55, 000	....	37, 100	23, 400	....
	....	55, 000	....	33, 000	21, 800	....
Averages	75, 888	49, 137	43, 980	34, 643	25, 350	22, 432

	2″ × 2″ × 1″	2″ × 2″ × 2″	2″ × 2″ × 4″	2″ × 2″ × 6″
Broken between wood cushions	40, 000	46, 000	37, 000	41, 000
	41, 000	45, 000	40, 200	40, 200
	42, 000	45, 000	33, 800	40, 200
	46, 000	44, 000	34, 600	39, 400
	39, 000	43, 000	40, 200	34, 600
	50, 000	44, 000	....	39, 400
	50, 000	40, 000	....	31, 400
	41, 000	....	....	....
	49, 000	....	....	....
	44, 000	....	....	....
	45, 000	....	....	....
	55, 000	....	....	....
	52, 000	....	....	....
	44, 000	....	....	....
Averages	45, 571	43, 857	37, 160	38, 028

TABLE IV.—*Resistance of blue Berea sandstone, &c.*—Continued.

	Steel.	Wood.	Lead.	Leather.
Slabs of 2″ × 2″ × 1″	75,000 61,800 70,200 71,200	49,200 48,800 43,200 47,800	37,800 26,200 29,000 30,000	17,000 19,000 22,320 27,400
Averages	69,550	47,250	30,750	21,430
Percentage	100	67.9	44.2	30.8

TABLE V.—*Beams 2″x 2″x 6″; bed 6″x 2″, resting on pine blocks, and broken by wrought-iron cylinder ½ inch diameter across center; supports 2½ inches apart.*

Granite. Millstone Point, Conn.	Marble. East Chester.	Granite. Keene, N. H.
4,000 to 4,500	4,000 to 4,200	3,300

Records not fully satisfactory, but sufficiently approximate for relative results. The East Chester marble and Keene, N. H., granite records can both be relied on; those of the Millstone Point granite cannot.

TABLE VI.—*Showing the difference in resisting power between stones broken with wooden-cushions—when their beds are polished—and stones with same pressing surface when only worked to clear beds.*

Kinds of stone.	Polished.	Unpolished.
Granite:		
Quincy, Mass	99,000	71,000
Staten Island, N. Y	100,000	89,000
Garrison's, N. Y	86,500	53,500
Tarrytown, N. Y	95,000	73,000
Millstone Point, Conn	91,500	75,000
Keene, N. H	79,333	51,000
Westerly, R. I	94,000	71,000
Difference 25 per cent., (nearly)	645,333	483,500
Marble:		
East Chester, N. Y	70,156	51,800
Vermont marble, Vt	43,400	35,000
Difference 25 per cent., (nearly)	113,556	86,800

TABLE VI*a*.—*General average percentage of the crushing-strength for various classes and qualities of stones referred to unpolished stones between wood cushions as a standard.*

	Polished stone crushed between cushions of—			
	Steel.	Wood.	Lead.	Leather.
For all kinds of polishable stones	147	133	97	93
	Unpolished stone crushed between cushions of—			
	Steel.	Wood.	Lead.	Leather.
Sandstones and unpolishable stones breaking above 10,000 pounds per square inch.	110	100	73	67
Between 10,000 and 8,000 pounds	100	100	83	....
Between 8,000 and 6,000 pounds	100	100	85	65
At 1,000 pounds per square inch.	100	100	100	100

GENERAL TABLE.

Crushing-strength of granites in two-inch cubes.

NOTE.—Stones marked (p) were all polished, broken with wooden cushion blocks, and 25 per cent. deducted in accord with results of Table VI, "Sundry experiments."

Number.	Kind.	Locality.	Position.	Cracked.	Strength of specimen.	Strength per square inch.	Specific gravity.	Weight of one cubic foot.	Ratio of absorption.	Remarks.
				Pounds.	*Pounds.*	*Pounds.*		*Pounds.*		
1	Blue	Staten Island, N. Y	On bed	24,000	89,000	22,250	2.861	178.8	Absorption too slow to be taken while weighing.	Cracked before bursting.
2		Fox Island, Me			59,500	14,875	2.631	164.1		Burst suddenly.
3		Dix Island, Me			60,000	15,000	2.635	166.5		Do.
4	Dark	Quincy, Mass		19,500	71,000	17,750	2.660	166.2		Cracked before bursting.
5	Light	do		18,000	59,000	14,750	2.695	168.7		Do.
6		Tarrytown, Westchester County, N. Y	On bed	22,000	73,000	18,250	2.655	162.2		Do.
7	Flagging	North River, N. Y			53,700	13,425	2.690	168.1		Broke suddenly without cracking.
8	Old Quarry	Westerly, Washington County, R. I			71,000	17,750	2.646	165.6		Do.
9	do	do			69,000	17,250	2.646	165.6		Do.
10		Millstone Point, Conn			64,750	16,187	2.706	168.7		Do.
11		do			75,000	18,750	2.706	168.7		Do.
12		Sprucehead, Me			54,000	13,500	2.750	171.9		Do.
13		do			70,000	17,500	2.750	171.9		Do.
14		Hewitt's Island, Me			57,500	14,375	2.634	164.6		Do.
15		do			60,250	15,062	2.634	164.6		Do.
16	Up river	Richmond, Va			85,000	21,250				Do.
17	do	do			80,000	20,000				Do.
18		Greenwich, Conn			45,200	11,300	2.835	177.2		Do.
19		do			46,800	11,700	2.835	177.2		Do.
20	Niantic River	New London, Conn			50,000	12,500	2.660	166.25		Do.
21	do	do	On edge		56,700	14,175	2.660	166.25		Do.
22		Fox Island, Me	On bed		60,250	15,062	2.660	166.3		Do.
23		do			46,800	11,700	2.660	166.3		Do.
24		Vinalhaven, Me			52,600	13,150	2.720	170.0		Do.
25		do			67,000	16,750	2.720	170.0		Do.
26	Harlem stone	Morrisania, Westchester County, N. Y			63,200	15,800	2.720	170.0		Do.
27	Tombstone	Sharkey's Quarry, Me			88,500	22,125	2.720	170.0		Do.
28	do	do			83,500	20,875	2.720	170.0		Do.
29		Richmond, Va			64,250	16,063	2.727	170.5		Do.
30		Cape Ann, Mass	On bed		59,750	12,423				Do.
31		do	do		78,000	19,500				Do.
32	Porter's rock	Mystic River, Conn	do		72,500	18,125	2.630	164.4		Do.
33	do	do	On edge		89,000	22,250	2.630	164.4		Do.
34	Gray	Westerly R. I	On bed		58,750	14,687	2.670	166.9		Do.
35	do	do	On edge		59,750	14,937	2.670	166.9		Do.
36	do	Richmond, Va	On bed		56,400	14,100	2.630	164.4	1-348	Do.
37	do	do	do		55,500	13,875	2.630	164.4	1-348	Do.

38	....do	New Haven, Conn	On edge	29,000	31,000	7,750	2.600	162.5	1-230	Waxy-looking, having a resinous luster.
39	....do	......do	On bed		38,000	9,500	2.600	162.5	1-230	Burst suddenly.
40	....do	Stony Creek, Conn	....do		60,000	15,000	2.645	165.4	1-201	Do.
41	....do	......do	On edge		67,000	16,750	2.645	165.4	1-201	Do.
42	....do	......do	On bed		63,000	15,750	2.645	165.4	1-201	Do.
43	....do	Fall River, Mass	....do		63,750	15,937	2.635	165.	1-216	Do.
44	....do	......do	On edge	33,000	37,000	9,250	2.635	165.	1-216	First split vertically.
45	Rose	Niantic, Conn	On bed		38,200	9,550	2.600	162.5	1-704	Burst suddenly; pores supposed filled with red pigment.
46	Gray	......do	....do		37,800	9,450	2.580	161.2	1-254	Burst suddenly.
47	Gneiss	Sachemshead Quarry, Conn	On edge		63,750	15,937	2.620	163.7	1-162	Do.
48	....do	......do	On bed		56,000	14,000	2.620	163.7	1-162	Do.
49	Gray	Hurricane Island, Me	....do	33,000	57,700	14,425	2.670	166.9	....	
50	....do	......do	On edge		59,750	14,937	2.670	166.9	....	Do.
51	....do	......do	On bed		44,000	11,000	2.670	166.9	....	Split off considerably before bursting.
52	Dark, soft-looking	Madison Avenue, N. Y	....do		45,000	11,250	2.920	182.5	0	Probably contains an unusual quantity of iron.
53	....do	......do	On edge		50,000	12,500	2,920	182.5	0	
54	Gray	Port Deposit, Md	On bed		79,000	19,750	2.720	170.	0	Coarse; strongly dashed with black.
55	....do	......do	On edge	33,000	52,400	13,100	2.720	170.	0	Do.
56	....do	......do	On bed		66,000	16,500	2.720	170.	0	Do.
57	....do	......do	....do		60,000	15,000	2.720	170.	0	Burst suddenly.
58	....do	Garrison's, North River, N. Y	On edge	48,000	49,000	12,250	2.580	161.3	1-167	
59	....do	......do	On bed	51,000	53,500	13,370	2.580	161.3	1-167	
60	....do	Palmer Quarry, Me	....do	41,000	46,000	11,500	2.590	161.9	1-150	
61	....do	......do	On edge	58,000	66,000	16,500	2.590	161.9	1-150	
62	....do	Rockport, Mass	On bed		65,200	16,300	2.610	163.2	1-152	
63	....do	......do	On edge	36,000	79,000	19,750	2.610	163.2	1-152	
64	Dark	Du Luth, Minn	On bed		71,000	17,750	2.780	173.7	1-711	Syenitic; or, perhaps, trap-rock.
65	....do	......do	....do		76,000	19,000	2.800	175.	0	
66	....do	......do	....do		67,300	16,825	2.800	175.	0	Scant.
67	Purplish	Huron Island, Mich	....do		72,500	18,125	2.630	164.4	1-659	
68	Grayish-rose	......do	....do		82,600	20,650	2.66	166.2	1-600	
69	.. do	......do	On edge		57,700	14,425	2.62	163.7	1-363	Soaked a week for absorption.
70	Grayish	Chaumont Bay, N. Y	On bed		91,000	22,750	2.65	165.	1-355	Do.
71	....do	......do	....do		64,200	16,050	2.65	165.	1-350	Do.
72	....do	......do	....do		70,000	17,500	2.66	166.2	1-557	
73	Dark	Du Luth, Minn	....do		68,000	17,000	(*)	(*)	(*)	
74	....do	......do	On edge		68,750	17,187	(*)	(*)	(*)	
75	Light	Saint Cloud, Stearns County, Minn	On bed		64,000	16,000	2.69	168.2	1-239	
76	....do	......do	On edge		74,000	18,500	2.69	168.2	1-239	
77	Bluish-gray	Keene, Cheshire County, N. H	On bed		41,000	10,375	2.656	166.	1-300	Used in inside of new capitol, Albany, N. Y.
78	....do	......do	....do		51,500	12,875	2.656	166.	1-300	
79	Light	Harbor Quarry, Me., (p)	....do		67,350	16,837	2.650	165.6	Not noticeable.	Boldly marked, resembling fine Breccia.
80	... do	......do	....do		64,875	16,218	2.650	165.6		Do.
81	... do	Dyer's Island, Me., (p)	....do		72,000	18,000	2.620	163.7		Do.
82	... do	......do	....do		72,000	18,000	2.620	163.7		Do.
83	Light gray	East Boston, Me., (p)	....do		64,125	16,031	2.630	164.4		Finely marked; bluish.
84	... do	..... do	....do		72,000	18,000	2.630	164.4		Do.
85	Whitish	City Point, Me., (p)	....do		60,375	15,093	2.650	165.6		Boldly marked, resembling fine Breccia.
86	.. do	......do	....do		60,000	15,000	2.650	165.6		Do.
87	Light	Carver's Quarry, Me., (p)	....do		60,375	15,093	2.575	161.0		Do.

(*) The absorption of most appears so small, and occurs so slowly, that they were left for soakage hereafter.

Crushing-strength of granites in two-inch cubes—Continued.

NOTE.—Stones marked (p) were polished, broken with wooden cushion blocks, and 25 per cent. deducted, in accord with Table VI, "Sundry experiments."

Number.	Kind.	Locality.	Position.	Cracked.	Strength of specimen.	Strength per square inch.	Specific gravity.	Weight of one cubic foot.	Ratio of absorption.	Remarks.
				Pounds.	*Pounds.*	*Pounds.*		*Pounds.*		
88	Light	Carver's Quarry, Me., (p)	On bed	....	53, 625	13, 406	2. 575	161. 0	Not noticeable.	Boldly marked, resembling fine Breccia.
89	....do	Wharf Quarry, Me., (p)	....do	....	61, 125	15, 281	2. 600	162. 5		Do.
90	....do	......do	....do	....	61, 200	15, 300	2. 600	162. 5		Do.
91	....do	K. W. & Co's Quarry, Me., (p)	....do	....	63, 375	15, 844	2. 620	163. 7		Do.
92	....do	......do	....do	....	64, 500	16, 125	2. 620	163. 7		Do.
93	Red	Bay of Fundy, Canada. (p)	....do	....	47, 250	11, 812	2. 600	162. 5		
94	....do	......do	....do	....	48, 075	12, 020	2. 600	162. 5		
95	....do	Used in Central Park, city of New York	....do	....	70, 000	17, 500	....	....		Fragment lost and specific gravity not taken.
96	....do	......do	On edge	....	75, 000	18, 750	....	....		Do.
97	Soap	Jersey City Heights, N. J	On bed	....	83, 000	20, 750	3. 03	189. 5		Very dark color.
98	....do	......do	....do	....	89, 000	22, 250	3. 03	189. 5		Do.
99	Gray	Pompton, Passaic County, N. J	....do	....	96, 160	24, 040	....	....		Average of three tests taken from near the surface. Quarry not opened.

Crushing-strength of limestones in two-inch cubes.

1	Glen's Falls	Glen's Falls, Warren County, N. Y	On bed	....	45, 900	11, 475	2. 700	168. 8	....	All the stones named below burst without cracking, except those noted to the contrary.
2	....do	......do	On edge	....	43, 000	10, 750	2. 700	168. 8	....	
3	Lake	Lake Champlain, N. Y	On bed	....	100, 000	25, 000	2. 75	171. 9	....	
4	... do	......do	On edge	60, 000	86, 000	21, 500	2. 75	171. 9	....	
5	....	Canajoharie, Montgomery County, N. Y	On bed	70, 000	82, 800	20, 700	2. 685	169. 8	....	
6	....	......do	On edge	70, 000	77, 000	19, 250	2. 685	169. 8	....	
7	North River	Kingston, N. Y	On bed	40, 000	55, 600	13, 900	2. 69	168. 2	....	
8	....do	......do	On edge	....	44, 200	11, 050	2. 69	168. 2	....	
9	....	Garrison's Station, N. Y	On bed	....	74, 000	18, 500	2. 635	164. 7	....	
10	....	......do	On edge	....	73, 100	18, 275	2. 635	164. 7	....	
11	....	......do	On bed	....	71, 000	17, 750	2. 62	163. 7	....	
12	....	......do	....do	....	71, 000	17, 750	2. 616	163. 5	....	
13	....	......do	....do	....	75, 100	18, 775	2. 616	163. 5	....	
14	White	Marblehead, Ohio	....do	....	45, 000	11, 250	2. 4	150.	1-30	
15	....do	......do	....do	....	42, 800	10, 700	2. 4	150.	1-33	
16	....do	......do	....do	....	50, 400	12, 600	2. 48	155.	1-33	
17	....do	Joliet, Ill	....do	....	51, 100	12, 775	2. 54	158. 8	1-51	
18	....do	......do	....do	....	67, 600	16, 900	2. 60	162. 5	1-139	
19	....do	......do	....do	....	58, 600	14, 650	2. 54	158. 8	1-91	
20	Drab	Lime Island, Mich	....do	....	72, 000	18, 000	2. 50	156. 3	1-76	

21	....do	......do	... do		100, 000	25, 000	2. 58	161. 2	1·139	
22	....do	......do	....do		61, 700	15, 425	2. 551	159. 4	1·56	
23	....do	Marquette, Mich	On edge		32, 200	8, 050	2. 34	146. 3	1·23	Rather a clay stone.
24	....do	......do	On bed		31, 300	7, 825	2. 34	146. 3	1·23	
25	....do	......do	On edge		30, 400	7, 600	2. 34	46. 3	1·23	
26	Bluish-drab	Big Sturgeon Bay, Wis	On bed		86, 000	21, 500	2. 78	173. 8	1·399	A remarkably solid, stable stone.
27	....do	......do	On edge		66, 750	16, 687	2. 75	171. 9	1·678	
28	....do	Lemont Quarry, Cook County, Ill	On bed		48, 000	12, 000	2. 645	165. 3	1·89	
29	.. do	......do	On edge		56, 000	14, 000	2. 645	165. 3	1·89	
30	Dark	Bardstown, Ky	On bed		65, 000	16, 250	2. 67	166. 9	1·80	Used for Louisville and Portland Canal.
31	....do	......do	On edge		60, 000	15, 000	2. 67	166. 9	1·80	Do.
32	White	Joliet, Ill	On bed		45, 000	11, 250	2. 55	159. 3	1·35	Specimens scant in measure, and not so good as Nos. 17 and 18 of same.
33	....do	......do	On edge		28, 200	7, 050	2. 55	159. 3	1·35	Do.
34	Dark drab	Billingsville, Cooper County, Mo	On bed		26, 600	6, 650	2. 32	145.	1·23	
35	....do	......do	On edge		29, 000	7, 250	2. 32	145.	1·23	
36	Blue	Williamsville, Erie County, N. Y	On bed		49, 000	12, 250	2. 64	165.	0	
37	....do	......do	On edge		49, 500	12, 375	2. 64	165.	0	
38	Caen	France	On bed		14, 600	3, 650	1. 900	118. 8	1·19	
39	....do	......do	....do		13, 800	3, 450	1. 900	118. 8	1·19	
40	Drab	Canton, Mo	....do		33, 800	8, 450	2. 34	146.	1·22	From two quarries, 1 and 2.
41	....do	......do	....do		37, 000	9, 250	2. 34	146.	1·22	Do.
42	....do	......do	....do		26, 600	6, 650	2. 34	146.	1·22	Do.
43	....do	......do	....do		22, 600	5, 650	2. 34	146.	1·22	Do.

Crushing-strength of marbles in two-inch cubes.

1	East Chester	Tuckahoe, Westchester County, N. Y	On bed		51, 800	12, 950	2. 875	179. 7	(*)	
2	....do	......do	....do		48, 200	12, 050	2. 875	179. 7	(*)	
3	Common Italian	Italy	....do		45, 000	11, 250	2. 690	168. 2	(*)	
4	....do	......do	....do		52, 250	13, 062	2. 690	168. 2	(*)	
5	Vermont	Dorset, Bennington County, Vt	....do		30, 450	7, 612	2. 635	164. 7	1·170	Crushed with slight explosion.
6	....do	......do	On edge		34, 680	8, 670	2. 683	167. 8	0	Do.
7	Drab	Mill Creek Quarry, Quincy, Ill	On bed		38, 750	9, 687	2. 570	160. 6	1·180	Crushed with louder explosion.
8	....do	......do	On edge		39, 150	9, 787	2. 510	156. 9	1·74	Do.
9	... do	North Bay Quarry, Door County, Wis	On bed		80, 100	20, 025	2. 900	175.	0	Crushed with quiet explosion.
10	....do	......do	On edge		54, 800	13, 700	2. 800	175.	0	Crushed with slight explosion; sand-cracks.
11	East Chester	Tuckahoe, Westchester Co., N. Y ..(p)	On bed		54, 375	13, 594	2. 800	175.	0	Whiter and of better quality than that shown above.
12	....do	......do ..(p)	....do		54, 844	13, 711	2. 800	175.	0	Position of quarry face lately changed.

Crushing-strength of sandstones in two-inch cubes.

1	Brown	Little Falls, N. Y	On bed		39, 400	9, 850	2. 250	140. 6	1·34	Used in building Trinity Church, New York City. Had been exposed for years to weather and become harder. Broke suddenly, without previous premonition.
2	...do	......do	On edge		36, 600	9, 150	2. 250	140. 6	1·34	

* The absorption of most appears so small, and occurs so slowly, that they were left for soakage hereafter.

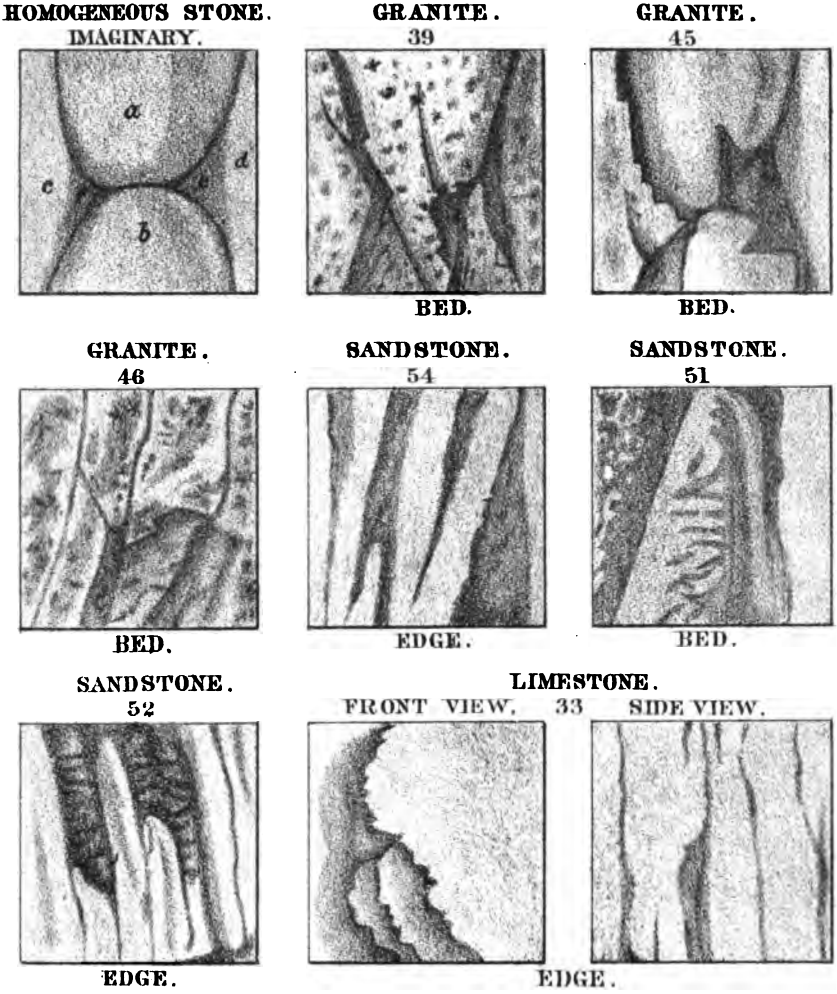
Crushing-strength of sandstones in two-inch cubes—Continued.

Number.	Kind.	Locality.	Position.	Cracked.	Strength of specimen.	Strength per square inch.	Specific gravity.	Weight of one cubic foot.	Ratio of absorption.	Remarks.
				Pounds.	*Pounds.*	*Pounds.*		*Pounds.*		
3	Gray	Bellville, N. J	On bed		46,800	11,700	2.259	141.	1-27	Broke suddenly.
4	...do	...do	On edge		41,000	10,250	2.259	141.	1-27	
5	Brown	Middletown, Conn	On bed		27,800	6,950	2.360	148.5	1-40	Trinity Church, Brooklyn, N. Y., built of it.
6	...do	...do	On edge		22,200	5,550	2.360	148.5	1-40	
7	Red	Haverstraw, N. Y	On bed		17,400	4,350	2.130	133.1	1-23	
8	...do	...do	On edge		16,100	4,025	3.130	133.1	1-23	
9	Pink	Medina, N. Y	On bed		69,000	17,250	2.410	150.6	1-55	Lilac in color.
10	...do	...do	On edge		59,250	14,812	2.390	149.3	1-51	More purple than last.
11	Drab	...do	On bed		70,900	17,725	2.420	151.1	1-70	
12	...do	Berea, Ohio	...do		41,000	10,250	2.110	131.9	1-16	Very friable, like sugar.
13	...do	...do	...do		33,200	8,300	2.130	133.1	1-20	
14	...do	...do	...do		29,000	7,250	2.200	137.5	1-24	
15	...do	...do	...do		31,000	7,750	2.110	131.9	1-19	
16	...do	...do	...do		38,400	9,600	2.140	133.7	1-22	
17	Brownish-gray	North Amherst, Ohio	On edge		21,800	5,450	2.140	133.7	1-19	
18	...do	...do	On bed		26,600	6,650	2.190	136.9	1-19	
19	...do	...do	...do		23,100	5,775	2.160	135.	1-19	
20	Drab	Vermillion, Ohio	...do		33,800	8,450	2.160	135.	1-19	
21	...do	...do	...do		33,000	8,250	2.165	135.3	1-19	
22	...do	...do	...do		24,000	6,000	2.165	135.3	1-19	
23	...do	...do	...do		35,400	8,850	2.157	134.8	1-19	
24	...do	...do	...do		31,400	7,850	2.157	134.8	1-19	
25	...do	...do	On edge		27,500	6,875	2.157	134.8	1-19	
26	Purple	Fond du Lac, Wis	On bed		25,000	6,250	2.220	138.8	1-22	
27	...do	...do	...do		24,900	6,225	2.220	138.8	1-22	
28	...do	...do	On edge		20,440	5,110	2.220	138.8	1-22	
29	...do	Bass Island, Wis	On bed		21,800	5,450	2.040	127.5	1-15	
30	...do	...do	...do		17,000	4,250	2.040	127.5	1-15	
31	...do	...do	On edge		17,150	4,287	2.040	127.5	1-15	
32	...do	Marquette, Mich	On bed		20,200	5,050	2.285	142.8	1-32	
33	...do	...do	...do		29,100	7,275	2.285	142.8	1-32	
34	...do	...do	On edge		22,600	5,650	2.285	142.8	1-32	
35	...do	...do	On bed		29,800	7,450	2.160	135.	1-20	
36	...do	...do	...do		29,800	7,450	2.160	135.	1-20	
37	...do	...do	On edge		22,920	5,730	2.160	135.	1-20	
38	...do	...do	On bed		21,000	5,250	2.170	135.6	1-20	
39	...do	...do	...do		25,080	6,270	2.170	135.6	1-20	
40	...do	...do	On edge		19,000	4,750	2.170	135.6	1-20	

41	Red-brown	Seneca freestone, Ohio	On bed		38, 750	9, 687	2. 390	149. 3	1-32	
42	....do	......do	On edge		42, 000	10, 500	2. 390	149. 3	1-32	
43	Olive-green	Cleveland, Ohio	On bed		27, 200	6, 800	2. 240	140.	1-37	
44	....do	......do	On edge		31, 640	7, 910	2. 240	140.	1-37	
45	Whitish	Marblehead, Ohio	On bed		31, 750	7, 937	2. 310	144. 4	1-19	Rather a chalky limestone.
46	....do	......do	On edge		27, 400	6, 850	2. 310	144. 4	1-19	Do.
47	Brown	Albion, Orleans County, N. Y	On bed		54, 000	13, 500	2. 420	151. 2	1-44	
48	....do	......do	On edge		45, 400	11, 350	2. 420	151. 2	1-44	
49	Pink	Kasota, Le Sueur County, Minn	On bed	27, 000	42, 800	10, 700	2. 630	164. 4	1-56	Calcareous sandstone.
50	....do	......do	On edge		46, 700	11, 675	2. 630	164. 4	1-56	
51	Light-buff	Fontenac, Goodhue County, Minn	On bed		25, 000	6, 250	2. 325	145. 3	1-28	
52	....do	......do	On edge		31, 100	7, 775	2. 325	145. 3	1-28	
53	Craigleith	Edinburg, Scotland	On bed		48, 000	12, 000	2. 260	141. 3	1-34	
54	....do	......do	On edge		45, 000	11, 250	2. 260	141. 3	1-34	
55	Freestone	Dorchester, New Brunswick	On bed		36, 600	9, 150				
56	....do	......do	....do		37, 650	9, 412				
57	Olive	......do	....do		17, 000	4, 250				
58	....do	......do	On edge		24, 200	6, 050				
59	Yellow drab	Massillon, Ohio	On bed		35, 000	8, 750	2. 110	131. 8	1-18	Average of two pieces. (See "Sundry Experiments.")
60	....do	......do	....do		26, 901	6, 725	2. 110	131. 8	1-18	Average of four pieces. Good for building-stone.
61	Bluish drab	Warrensburg, Mo	....do		20, 000	5, 000	2. 140	133. 7	1-20	Easy-working freestone. Clear grain. Gets harder by time and exposure.
62	....do	......do	....do		19, 750	4, 937	2. 140	133. 7	1-20	

PLATE 1.

DIAGRAM OF CRUSHED CUBES OF STONE.



HOMOGENEOUS STONE. IMAGINARY.

GRANITE. 39 BED.

GRANITE. 45 BED.

GRANITE. 46 BED.

SANDSTONE. 54 EDGE.

SANDSTONE. 51 BED.

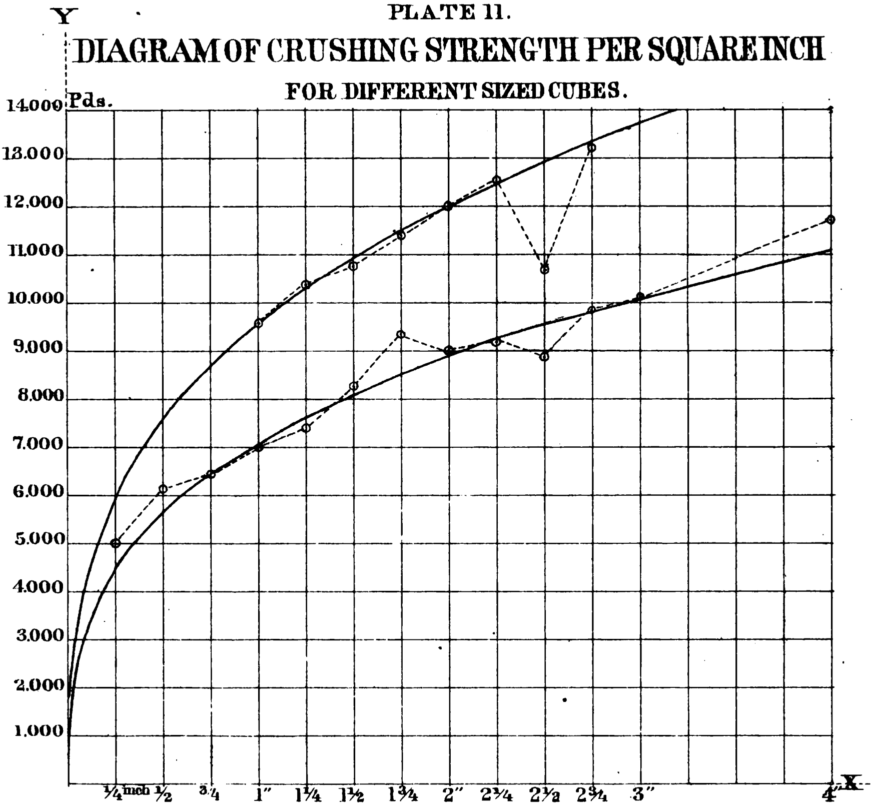
SANDSTONE. 52 EDGE.

LIMESTONE. FRONT VIEW. 33 SIDE VIEW. EDGE.

PLATE 11.

DIAGRAM OF CRUSHING STRENGTH PER SQUARE INCH

FOR DIFFERENT SIZED CUBES.



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